PHYTOPLANKTON BIOMASS AND COMMUNITY STRUCTURE AT FRONTAL ZONES IN THE SURFACE WATERS OF THE NORTHERN GULF OF MEXICO

A Thesis

by

ALICIA SALAZAR

Submitted to the Office of the Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Oceanography

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Approved as to style and content by:

James L. Pinckney (Chair of Committee)	Tammi L. Richardson (Member)
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ABSTRACT

Phytoplankton Biomass and Community Structure at Frontal Zones in the Surface Waters of the Northern Gulf of Mexico. (December 2004)

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Chair of Advisory Committee: Dr. James L. Pinckney

Satellite images of chlorophyll concentration in the surface waters of the Gulf of Mexico suggest a high degree of heterogeneity in the phytoplankton biomass. The causes of this variability and the amount of variability in the phytoplankton community structure are not well understood. The physical and chemical conditions of a specific environment can influence phytoplankton community structure by selecting for those phytoplankton species able to survive within that environment. Varying salinity and temperature characteristics give water masses distinct surface water density signatures. This study examined the relationship between phytoplankton biomass, community structure, and different water mass properties by measuring chlorophyll *a* and algal group concentration across frontal zones.

Continuous salinity and temperature measurements were used to calculate continuous density along transects during four cruises on the R/V *Gyre* between summer 2002 and spring 2004. Frontal zones were identified as areas of sharp density change where σ_t changed by 1.5 points over a distance of 1 km. Density fronts that coincided with visible temperature fronts (satellite AVHRR images) were selected for

biomass and community structure analysis. Discrete water samples were analyzed using fluorometric analysis (total chlorophyll *a* concentration) and HPLC analysis (photosynthetic pigments). Community composition for discrete samples was determined using CHEMTAX and these values were used to interpolate community composition.

Phytoplankton biomass and community structure were examined at a total of 21 density fronts. Unlike previous studies of frontal zones, phytoplankton biomass (measured as chl *a* concentration) was not significantly higher within frontal zones than in adjacent waters at any of the 21 fronts. Community composition (measured as algal group abundance and diversity) was significantly different between the front and at least one adjacent water mass at front 2 during summer 2002, at front 6 during summer 2003, at front 3 during fall 2003, and at front 3 during spring 2004. Both biomass and community composition were significantly different between fronts at all front pairs during summer 2002. The results of this study suggest that density fronts are not biologically important features in the northern Gulf of Mexico. Lack of high phytoplankton biomass at fronts in the Gulf of Mexico could indicate that unique physical, chemical, or biological processes are occurring.

DEDICATION

This work is dedicated to family and friends without whose understanding and support it would not have been possible.

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The data used in this thesis was collected during two MMS sponsored Sperm Whale Seismic Study cruises and two NOAA sponsored Hypoxia cruises. I would like to thank Dr. Doug Biggs and Dr. Steve DiMarco for giving me the chance to participate in those cruises and to collect data for my own research. I would also like to thank Dr. Ann Jochens contributing her knowledge about circulation in the Gulf of Mexico.

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INTRODUCTION

A number of physical and chemical regimes exist within the Gulf of Mexico (GOM) making it ideal for studying the relationships between these regimes and the biomass and community structure of phytoplankton. Coastal waters of the GOM are influenced by the discharge of fresh, nutrient-rich water from rivers such as the Mississippi River (Ho and Barrett 1977). The Mississippi River, along with its distributary, the Atchafalaya River, drains approximately 41% of the area of the continental US and discharges about 580 km^3 yr^{-1} (Walker et al. 1994; Rabalais et al. 1996). The Gulf sees an annual occurrence of a zone of hypoxia/anoxia that has reached over 20,000 km^2 and that is hypothesized to result from the high nitrate concentrations in the Mississippi River plume (Dortch et al. 1994; Rabalais et al. 1996; Rabalais et al. 2002). Offshore waters as well as southern shelf waters are oligotrophic (Barnard and Froelich 1981). In addition, the GOM is invaded to the south by the loop current (Nowlin et al. 1998). Eddies from the loop current pinch off and move westward, bringing warm, oligotrophic water into the northeastern Gulf of Mexico (Biggs, 1992; Biggs et al. 1994). Upwelling by cold core eddies can bring nutrient rich water to the surface, while downwelling by warm core eddies adjacent to the shelf can entrain riverine water offshore (Falkowski et al. 1991; Gilbes et al. 1996; Qian et al. 2003).

This thesis follows the style and format of Marine Ecology Progress Series.

Fronts

When two water masses with distinct properties meet, a third water mass is formed, called a front. The two adjacent water masses are essentially two separate ecosystems and the zone created by mixing along the edges is a unique ecosystem, or an ecotone (Odum 1971).

Enhanced phytoplankton biomass often occurs at fronts—defined as regions of strong horizontal temperature and/or salinity contrast (Franks 1992a; Franks 1992b; Laubscher et al. 1993; Flint and Sukhanova 2002). Fronts can be permanent—such as the Subtropical Front and the Sub-Antarctic Front in the South Indian Ocean (Fiala et al. 2003; Kopczynska and Fiala 2003)—or they can be temporary—such as coastal tidal fronts (Dustan et al. 1989; Pinckney et al. 1990; Flint et al. 2002). The enhanced biomass present at fronts could be a result of increased nutrient uptake or increased growth rate in response to higher nutrient concentrations (Franks 1992b). Enhanced biomass could also be due simply to transport mechanisms. For example, biological enhancement at fronts could be due to the physical accumulation of phytoplankton brought about by the convergence of surface waters (Olson and Backus 1985). Franks (1992b) reported that some enhancement of biomass could be caused by a directed swimming behavior within the dynamic frontal region, independent of physiological responses of the organism. Some phytoplankton can have swimming speeds ranging from several μm (cyanobacteria *Synechococcus*, 25μm/s) to mm (dinoflagellate *Protoperidinium*, 8.3 mm/s) per second (Ehlers et al. 1996; Jeong et al. 2004). Motile phytoplankton are often directed by a gradient in various properties such as light,

temperature, salinity, nutrients, or particle concentration resulting in biomass accumulation at the front due to retention or accumulation (Franks 1992b; McGillicuddy et al. 2003; Hetland et al. 2002). Gradients in one or more of these properties are often associated with frontal zones. The type of gradient depends on the type of front. Fronts created by coastal upwelling usually exhibit a sharp change in temperature, water mass fronts exhibit gradients in salinity, tidal fronts can have strong gradients in light, temperature and nutrients, and topographic fronts show strong temperature contrast (Franks 1992b).

Several additional studies have demonstrated changes in phytoplankton community structure at fronts. Pingree et al. (1975) studied the phytoplankton blooms at tidal fronts around the British Isles and found that they were dominated by large dinoflagellate blooms. Flint et al. (2002) compared cell counts of phytoplankton species to abundance distribution (10^3 cell/L) of phytoplankton groups in three identified coastal regimes: coastal zone, coastal front, and middle shelf. This group found that the high phytoplankton biomass found at fronts was dominated by a limited set of diatom species. Kopczyńska et al. (2003) also studied phytoplankton biomass as well as algal group abundance in the Crozet Basin. In addition to finding higher biomass within the Subtropical Front (STF), they found that the high phytoplankton biomass within the STF was dominated by both dinoflagellates and diatoms.

Major Influences on Phytoplankton Biomass and Community Structure

Light: Light intensity can have a significant effect on photosynthesis (Litchman 2000; MacIntyre et al. 2002). Both increases and decreases in light intensity can limit

photosynthesis. High light intensities can induce photoinhibition, while low light intensities can lead to insufficient energy for photosynthesis (Osmond 1994; Falkowski and LaRoche 1991). Light regimes typically vary according to time of day, season, water depth, and turbidity, with the highest light intensities present at mid-day, during the summer, and in non-turbid surface waters. The process whereby phytoplankton adjust their photosynthetic pigment concentration in response to irradiance is called photoacclimation (Falkowski et al. 1997; MacIntyre et al. 2002). In phytoplankton adapted to low light, a sudden change in light intensity can lead to inhibition of photosynthesis. The amount of adaptation to certain light level is different for different algal groups. For example, cyanobacteria are generally adapted to low light, while dinoflagellates are adapted to high light (Parsons et al. 1984).

Temperature: Many phytoplankton live within specific temperature limits. For example, diatoms and haptophytes have high maximal growth rates at low temperatures, and therefore tend to dominate in polar and subpolar regions (Kang et al. 1991). *Synechococcus* and *Prochlorococcus*, on the other hand, have adapted to growth at warmer temperatures in tropical and subtropical regions (Olson et al. 1990; Campbell et al. 1994). Growth rate versus temperature curves for five different phytoplankton species were compiled by Eppley (1972) showing that each species exhibited a different optimum temperature for growth. Given phytoplankton specificity with regard to temperature, changes in temperature could affect community structure by allowing the best adapted group of phytoplankton to flourish within different temperature regimes. Laubscher et al. (1993) showed that the phytoplankton assemblages at the Subantarctic

and Antarctic Polar Fronts in the Southern Ocean were dominated by diatoms (*Chaetoceros* spp. and *Nitzschia* spp.) in the early summer and by a combination of nanophytoplankton and diatoms (*Corethron* criophilum) at the Anarctic Front) in the late summer. They concluded that the increase in total biomass was probably the result of an enhancement of *in situ* production by these specific groups in response to silicate concentrations and water-column stability and not of transport by physical processes.

Salinity: Salinity is auto-correlated with nutrient content, therefore can influence phytoplankton biomass and community structure indirectly. Low salinity river water is often found to be nutrient rich while high salinity open ocean water is often depleted in nutrients. The association between phytoplankton community structure and salinity has been documented in several studies. For example, in a study of the spatial and temporal variations of phytoplankton biomass and community structure in the northeast Gulf of Mexico, Qian et al. (2003) found that diatoms, chlorophytes and cryptophytes were associated with low salinity waters, while prymnesiophytes and pelagophytes were associated with high salinity waters. Both nitrate and phosphate concentrations were found to be below the threshold of nutrient limitation for phytoplankton growth at all stations except those near the mouths of the Mississippi and Apalachicola Rivers. In a study comparing the vertical structure of the phytoplankton community within and outside a coastal plume in the GOM, Wawrik et al. (2003) found that the Mississippi River plume could dramatically alter the surface picoplankton composition of the GOM, with *Synechococcus* displacing *Prochlorococcus* in the surface waters within the plume possibly due to the lower salinity of these waters. This

effect could be due to the fact that surface waters are more strongly influenced by freshwater (low salinity) input due to water column stratification. Water column stratification occurs because rivers such as the Mississippi River discharge lower density freshwater which is buoyant and does not mix with the higher density saltwater deeper in the water column (Narayanan et al. 2002).

Nutrients: The variable pattern of shelf circulation exerts a strong influence on the distributions of physical and chemical properties over the GOM shelf (Chen et al. 2000) which can influence the biomass and community structure of phytoplankton by bringing nutrient rich water into usually oligotrophic areas. Different phytoplankton groups have different requirements for dissolved nutrients such as nitrate, phosphate, and silicate (Eppley et al. 1969; Guillard et al. 1973; Ducobu et al. 1998). These varying requirements make the nutrient concentration in specific water masses important in shaping the composition of the local phytoplankton community (Tilman 1982; Sommer 1989; Ducobu et al. 1998). Changes in nutrient concentrations due to nutrient additions (by river discharge, atmospheric deposition, upwelling or mixing) or nutrient losses (due to consumption by phytoplankton blooms or denitrification) can alter phytoplankton communities by affecting the competitive balance for limiting resources. Several physical processes control the circulation of waters of different nutrient concentrations onto the Texas-Louisiana shelf: (1) riverine discharge, (2) bay discharge, and (3) shelf-edge upwelling caused by a northeastward current on the outer shelf (Sahl et al. 1993). Additionally, periodic upwelling caused by loop current eddies that move onto the shelf can bring nutrient-rich deep water to the surface (Biggs 1992). Downwelling caused by

loop current eddies adjacent to the shelf can pull high nutrient, low salinity river water off of the continental shelf (Muller-Karger et al. 1991, Gonzalez-Rodas 1999; Hu et al. 2003). The lack of specific nutrients can also alter community composition. Iron-limitation can lead to a shift from large, thickly, silicified diatoms to smaller, lightly silicified diatoms (Kopczyńska 2003). This shift in cell size from large to small can lead to a shift in community composition because reduced cell size can lead to a greater susceptibility to predation by mesozooplankton (DiTullio 2003). Higher grazing pressure on one species can shift dominance to another species with less grazing pressure.

Phytoplankton nutrient requirements: The effects of varying environmental nutrient concentrations and varying nutrient requirements of different algal groups have been studied extensively. For example, Örnólfsdottir et al. (2004a) studied the effect of nitrate and phosphate (N+P) pulses on estuarine phytoplankton growth rate and community structure in Galveston Bay and found that phytoplankton community composition was significantly different between control and N+P treatments. They found that the relative abundance of diatoms increased in N+P treatments while that of cyanobacteria, cryptophytes, and chlorophytes remained constant or decreased. Diatoms have often been shown to be associated with high nutrient concentrations typically associated with riverine inputs or upwelling, while cyanobacteria are associated with lower nutrient concentrations (Hallegraeff 1981; Tilman et al. 1986; Örnólfsdottir et al. 2004b). Haptophytes also have a higher nutrient requirement and tend to dominate in high nutrient, low temperature areas (Kang et al. 1991), while prymnesiophytes have

been associated with higher nutrient areas (Barlow et al. 1997). Dinoflagellates may have low nutritional requirements and are sometimes associated with nutrient poor environments (Aubry et al. 2004). The red tide dinoflagellate *Karenia brevis* which periodically blooms along the Gulf Coast in Texas and Florida, for instance, is adapted to growth at low nitrate and phosphate concentrations (Vargo et al. 1990; Steidinger et al. 1998).

Grazing: Grazing can influence phytoplankton biomass by controlling the total concentration of phytoplankton (Franks 2001). In the Gulf of Mexico, zooplankton grazing of phytoplankton is dominated by protozoa, gelatinous zooplankton, and copepods (Dagg et al. 2003). Microzooplankton grazing rates on phytoplankton cells <20 μm have been reported as 82% of algal growth rates in some areas of the GOM (Fahnenstiel et al. 1995). Dagg (1995) reported copeod grazing rates of 14-62% of daily algal production in the northern GOM. If zooplankton graze only on specific algal groups, then intense grazing can also affect community structure (Dagg 2003).

Pigments as Biomarkers

The primary factors controlling the distribution and abundances of phytoplankton groups in the GOM can be examined by quantifying the concentration and composition of phytoplankton communities over large spatial scales. Chemical biomarkers such as taxa-specific photopigments have been widely used as a means of estimating phytoplankton biomass as well as identifying different algal classes in marine ecosystems (Letelier et al. 1993; Jeffrey et al. 1997; Mackey et al. 1998; Wright et al. 2000). Different groups of phytoplankton contain specific photopigments in different

combinations, making it possible to identify which algal groups are present in a water sample by identifying the concentrations of different diagnostic photopigments (Millie et al. 1993; Mackey et al. 1996, 1998; Wright et al. 1996; Pinckney et al. 1998). Table 1 shows some common groups of phytoplankton and their diagnostic pigments.

Table 1. Common algal groups and their diagnostic pigments.[1]

Algal Groups	Photopigments
Cyanobacteria	Zeaxanthin, Allophycocyanins, Phycocyanins, Phycoerythrins
Prochlorophytes	Divinyl chl *a*, Divinyl chl *b*, Zeaxanthin
Rhodophytes	Zeaxanthin, Allophycocyanins, Phycoerythrins
Cryptophytes	Chl c_2, Alloxanthin, Phycocyanins, Phycoerythrins
Chlorophytes	Chl *b*, Lutein, Neoxanthin, Violaxanthin
Prasinophytes	Chl *b*, Neoxanthin, Prasinoxanthin, Violoxanthin
Euglenophytes	Chl *b*, Diadinoxanthin,
Bacillariophytes	Chl c_1, Chl c_2, Diadinoxanthin, Fucoxanthin
Dinoflagellates	Chl c_2, Diadinoxanthin, Peridinin
Prymnesiophytes	Chl c_1, Chl c_2,Chl c_3, 19'-Butanoyloxyfucoxanthin, Diadinoxanthin, Fucoxanthin, 19'-Hexanoyloxyfucoxanthin,
Chrysophytes	Chl c_2, Chl c_3, 19'-Butanoyloxyfucoxanthin, Diadinoxanthin, Fucoxanthin
Raphidophytes	Chl c_1, Chl c_2, Diadinoxanthin, Fucoxanthin
Haptophytes	19'-Butanoyloxyfucoxanthin, Fucoxanthin, 19'-Hexanoyloxyfucoxanthin, Neoxanthin, Diadinoxanthin,

[1]Jeffrey et al. 1997; Mackey et al. 1998

Pigments were used by Mackey et al. (1996) to estimate the phytoplankton community structure using synthetic data-sets of HPLC pigment concentrations and corresponding algal class abundances. Photopigment concentrations have also been used in various studies to determine the algal composition of field samples (Wright et al. 1996; Barlow et al. 1997; Pinckney et al. 1998). These studies illustrate the common use of photopigments as biomarkers for different algal groups.

Approaches for Partitioning Chlorophyll a *into Algal Groups*

One of the simplest approaches to identifying algal groups using pigment concentration was used by Barlow et al. (1997). They studied pigment chemotaxonomic distributions of phytoplankton in the western Mediterranean by identifying photopigments present using HPLC and then relating major accessory pigments to appropriate phytoplankton classes using the relationships listed in Table 2.

Table 2. Photopigment/Phytoplankton associations used to study phytoplankton distribution in the western Mediterranean.[1]

Algal Groups	Associated Photopigment
Dinoflagellates	Peridinin
Chrysophytes/Pelagophytes	Butanoyloxyfucoxanthin
Diatoms	Fucoxanthin
Prymnesiophytes	Hexanoyloxyfucoxanthin
Cryptophytes	Alloxanthin
Cyanobacteria/prochlorophytes	Zeaxanthin
Chlorophytes/Prochlorophytes/Prasinophytes	Chlorophyll *b*
Prochlorophytes	Divinyl chlorophyll *a*

[2]Barlow et al. (1997)

Recently, however, two more analytical approaches have been used.

Algorithms: One common approach to determining community structure using diagnostic pigments is the use of algorithms. Algorithms use concentrations of each pigment biomarker found in a sample to solve a set of simultaneous equations. Each equation determines the contribution of a single algal group. In each equation, contributions from shared biomarkers (pigments found in several algal groups) are subtracted from the estimated contribution of the diagnostic pigment (pigments specific to one algal group) to allow for overlapping compositions (Wright et al. 2000; Gieskes and Kraay, 1986; Gieskes et al. 1988; Letelier et al. 1993). Qian et al. (2003) used this method to compare physical and chemical characteristics with pigment distributions in

the GOM. They used chlorophyll and carotenoid pigment distributions to describe spatial and temporal variations in phytoplankton biomass in the water column of the northeastern GOM. Qian et al. (2003) used pigment algorithms derived from Letelier et al. (1993), Andersen et al. (1996), Mackey et al. (1996), and Wright and van den Enden (2000) to partition chlorophyll *a* biomass among the major phytoplankton groups (Table 3).

Table 3. Pigment algorithms used for partitioning chlorophyll *a* biomass among the major phytoplankton groups[3]

Algal Groups	Chl *a*/pigment seed values		Equations
Prokaryotes	Chl *a*:Chl *b*	2.5	$[\text{Chl } a]_{prokr}=[\text{Zeax}]+0.5\ [\text{Chl } b]$
	Zea:Chl *b*	0.3	
Prymnesiophytes	Chl *a*:19'-hex	1.6	$[\text{Chl } a]_{prymn}=1.3[19'\text{-Hex}]-0.1[19'\text{-But+Fuco}]$
	Fuco:19'-hex	0.05	
	19'-hex:19'-but	54.27	
Pelagophytes	Chl *a*:19'-but	3.82	$[\text{Chl } a]_{pela}=0.9[19'\text{-But}]-0.02[19'\text{-Hex}]$
	Fuco:19'-but	1.39	
	19'-hex:19'-but	0.14	
Dinoflagellates	Chl *a*:perid	1.55	$[\text{Chl } a]_{dino}=1.5[\text{Perid}]$
Diatoms	Chl *a*:fuco	0.8	$[\text{Chl } a]_{diat}=0.8\{[\text{Fuco}]-(0.02[19'\text{-hex}]+0.14[19'\text{-but}]\}$
Chlorophytes	Chl *a*:viol	9.2	$[\text{Chl } a]_{chlor}=9[\text{Viol}]$
Cryptophytes	Chl *a*:allox	4.3	$[\text{Chl } a]_{cryp}=4[\text{Allox}]$
Prasinophytes	Chl *a*:prasino	2.54	$[\text{Chl } a]_{pras}=2.1[\text{Prasino}]$
	Chl *b*:prasino	2.62	

[3]Letelier et al., 1993; Andersen et al., 1996; Mackey et al., 1996; Wright and van den Enden, 2000)

Lambert et al. (1999) used algorithms to study cross-shelf changes in phytoplankton community structure in the GOM. Known chlorophyll *a*/xanthophylls or chlorophyll *b* ratios from referenced algal cultures were used along with the algorithms of Letelier et al. (1993) (Table 4) to estimate the relative contribution of different algal classes to total chlorophyll *a*.

Table 4. Pigment algorithms used for partitioning chlorophyll *a* biomass among major phytoplankton groups.

Algal Groups	Equations	Algal Culture Source
Diatoms	$[\text{Chl } a]_{diat}=0.8\{[\text{Fuco}]-(0.02[19'\text{-hex}]_{prym}+0.14[19'\text{-but}]_{pela})\}$	*Phaeodactylumn tricornutum* (CCMP 1327)
Cyanobacteria	$[\text{Chl } a]_{cyano}=2.1\{[\text{zeax}]-0.07[\text{Chl } b]\}$	Kana et al. (1988)
Pelagophytes	$[\text{Chl } a]_{pela}=0.9[19'\text{-but}]$	Clone 1935-1 (CCMP 1145)
Prymnesiophytes	$[\text{Chl } a]_{prym}=1.3[19'\text{-Hex}]$	*Emiliana huxleyi* (CCMP 373)
Dinoflagellates	$[\text{Chl } a]_{dino}=1.5[\text{Perid}]$	*Pycnococcus provasolii* (CCMP 1203)

[4](Lambert et al. 1999)

CHEMTAX: The CHEMTAX program also utilizes diagnostic pigments to partition total chlorophyll *a* into individual algal groups. CHEMical TAXonomy is a matrix-factorization program for calculating algal class abundances from concentrations of algal photopigments (Mackey et al. 1996, 1998; Wright et al. 1996). CHEMTAX uses factor analysis and a steepest descent algorithm to find the best fit to the data based on an initial estimate of the pigment ratios for the classes to be determined (Mackey et al. 1996; Lohrenz et al. 2003). The raw data used for the program are photopigment concentrations obtained by HPLC analyses and initial pigment ratios. Initial pigment ratios for each pigment present in the sample are used by CHEMTAX to calculate the fraction of total chl *a* due to each phytoplankton group. Initial pigment ratios are an estimate the ratio of pigment per chlorophyll *a* found in major groups of phytoplankton (Mackey et al. 1996). The initial pigment ratio matrix for this study was determined using initial pigment ratios reported by Mackey et al. (1996). The class composition matrix can be expressed as relative or absolute values for specified photopigments

(Pinckney et al. 1998). A full discussion of the procedures used, validation and sensitivity analyses can be found in Mackey et al. (1996).

Gibb et al. (2001) used CHEMTAX to study phytoplankton pigment chemotaxonomy of the northeastern Atlantic. Gibb et al. (2001) used input ratio matrices built from taxon specific marker pigment:CHL*a* ratios in Mackey et al. (1997). They found that prymnesiophytes, cryptophytes, chlorophytes, and diatoms dominated in high chlorophyll areas, while cyanobacteria and prochlorophytes dominated in oligotrophic areas.

Algorithms v. CHEMTAX: While algorithms provide an accurate estimate of the contribution of single pigment markers, CHEMTAX provides a better estimate of the relative abundances of different algal groups. As discussed, algorithms use separate equations for each algal group and determine composition by subtraction of shared biomarkers. CHEMTAX, on the other hand, compares all of the pigments present to each other using a matrix of pigment ratios representative of the algal groups typically found in a study area to provide an estimate of community structure (Wright et al. 2000). Thus, CHEMTAX provides a better estimate of algal group abundance than the algorithm method because it calculates abundance based on the fraction of chl *a* represented by each pigment relative to each other pigment present.

Diversity

Measurements of diversity provide a method for analyzing changes in community structure. Diversity is used as an abridged expression of how a set (in this case, a community of phytoplankton) is distributed into subsets (in this case, major algal

groups) (Margalef 1978). Phytoplankton community structure is formed by competition for resources and grazing pressure (Titman 1976; Goericke 2002). The dynamics of this competition have been explained using several theories including the principle of competitive exclusion (Hardin 1960) and intermediate disturbance theory (Tilman 1977; Sommer 1995; Sommer 1999). Each of these theories provides an explanation for how one or a few groups of phytoplankton establish dominance over other groups. When dominance changes, diversity can change. The result is that changes in diversity can reflect changes in community structure. The Shannon-Weaver Index is one of several indices which provide a formula for quantifying diversity (Margalef 1978). The formula is:

$$H = -\sum_{i=1}^{s} P_i \ln P_i \qquad (1)$$

Where H is diversity, P_i is equal to N_i/N, N_i is the number of individuals of species I, and N is the total number of individuals in the sample or ecosystem. This formula can be adjusted for calculations of phytoplankton diversity by replacing numbers of individuals with concentrations of photopigments. The resulting values range from 1 to 2.5 in coastal waters (low diversity) and 3.5 to 5 in oceanic waters (high diversity) (Margalef 1978).

Continuous Fluorescence Data and Remote Sensing

The distribution of phytoplankton is characterized by high spatial and temporal variability making it difficult to construct basin-wide maps of phytoplankton biomass (Thomas et al. 2003). Remote sensing provides measurements of concentrations of

chlorophyll *a* over a wide area using ocean color. The resulting satellite images provide an estimate of surface phytoplankton biomass as chl *a* concentration, but do not provide information on the abundance of different algal groups. This study uses a method for estimating relative algal abundance based on chlorophyll *a* concentrations calculated from fluorescence data. Continuous fluorescence data which have been converted to algal group abundance estimates can complement remote sensing data by providing a breakdown of total chlorophyll *a* into representative algal groups.

Objectives

The purpose of this study was to examine the relationship between phytoplankton and the different physical and chemical regimes in the Gulf of Mexico by looking at changes in biomass and community structure at fronts (where two water masses with different properties meet). Most studies of phytoplankton biomass and community structure depend on discrete samples taken at isolated stations. This study uses continuous fluorometry data together with HPLC data to estimate continuous community composition in the surface waters of the northern Gulf of Mexico. The goal is to identify patterns in phytoplankton biomass and community structure and to relate those patterns with changes in water mass properties across frontal zones. Continuous data could eventually complement satellite color images of chlorophyll and provide a broader estimate of community structure over larger areas.

MATERIALS AND METHODS

Data Collection

During the course of two summer cruises in 2002 and 2003, one fall cruise in 2003, and one spring cruise in 2004, water samples were taken for analysis by fluorometry and HPLC. The summer 2002 cruise was a survey in the northern GOM along the 1000 m isobath between 94°W and 86°W. The summer 2003 cruise was also a survey along the 1000 m isobath between 95°W and 86° W. The fall 2003 and spring 2004 cruises surveyed between 93°W and 90°W along portions of the Texas-Louisiana coast influenced by the Mississippi River plume. The Spring 2004 cruise surveyed between 93°W and 89°W in areas usually affected by hypoxia during summer. Continuous measurements of surface temperature and salinity were taken by sampling water from an intake extending from the just off the midship at the R/V Gyre's hull depth of 3.5 meters using Seabird temperature and conductivity sensors. Continuous measurements of *in vivo* chlorophyll fluorescence were obtained using a Turner Designs Model 10 fluorometer equipped with a flow-through cell. The sampling interval was fixed at one minute. At each station along a survey route (shown below in Figures 1, 2, and 3, and 4 respectively), totaling approximately 40 stations in summer 2002, 73 stations in summer 2003, 36 stations in fall of 2003, and 18 stations in 2004, a sample of water (0.2 L – 3 L) was collected from a surface pump at 3.5 m depth and filtered under low pressure vacuum (<200 mm Hg) for analysis by HPLC. During the summer 2002 and 2003 cruises, 1 L of water was also collected from the surface pump and filtered under a low pressure vacuum for analysis by fluorometry.

Pigment concentrations partitioned into algal groups were used to compare algal abundances in different areas of the GOM. Concentrations of carotenoids and chlorophyll *a* in algal cells are influenced by irradiance and nutrient limitation (Goericke et al. 1998). The reliability of the results of photopigment analysis depends on initial pigment ratios chosen as input to the CHEMTAX software (Mackey et al. 1996; Schluter et al. 2000). Provided that input ratio files reflect the dominant phytoplankton groups in the sample, the CHEMTAX program is a robust method for determining algal abundance based on photopigment concentration (Mackey et al. 1996, 1998; Wright et al. 1996; Schluter 2000 et al). I used an initial pigment ratio matrix derived from those compiled by Mackey et al. (1996). The matrix for each set of data was determined by the pigments present.

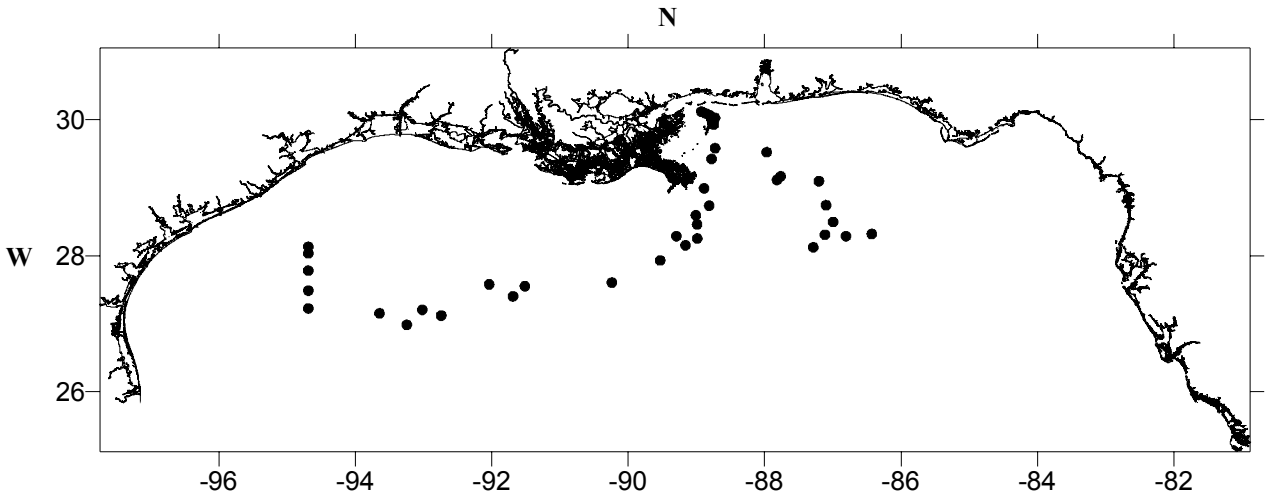

Figure 1. Survey area for the 2002 summer cruise. Ship surveyed along the 1000 m isobath between 95°W and 86°W, then turned in toward Gulfport, Mississippi. Each point represents a sampling station.

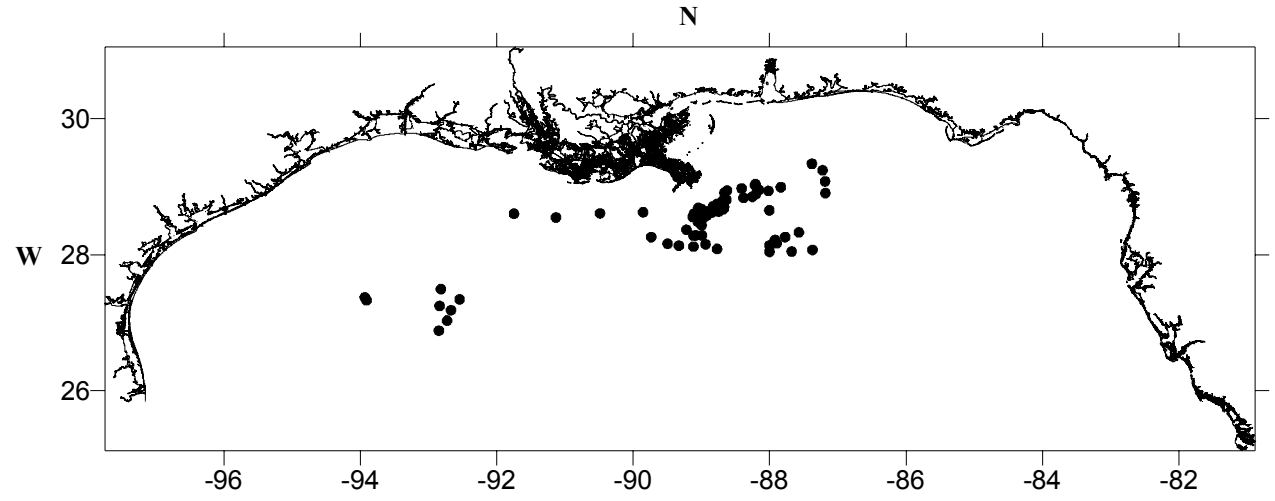

Figure 2. Survey area for the summer 2003 cruise. Survey began at 1000 m isobath and included the area between 95°W and 86°W. Ship's track was altered according to the location of Sperm whales.

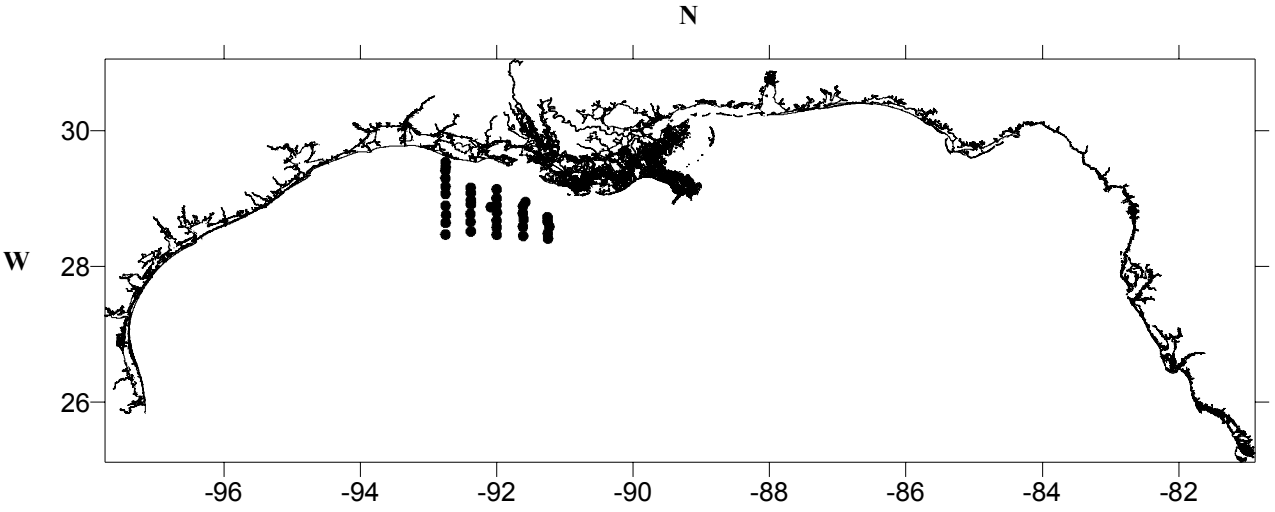

Figure 3. Survey area for the fall 2003 cruise. Ship surveyed the area between 93°W and 91°W.

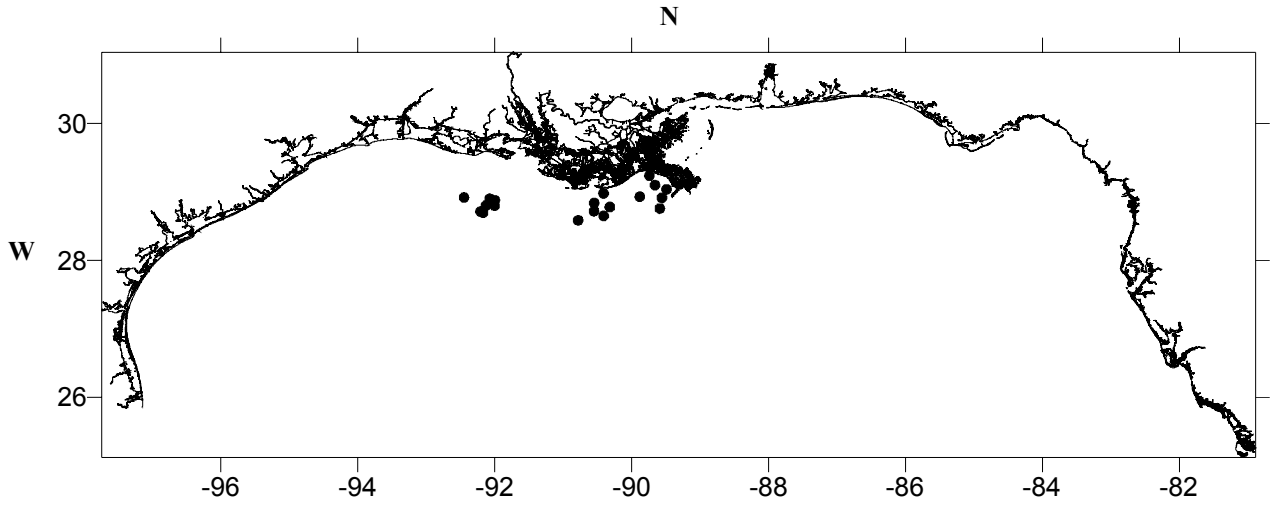

Figure 4. Survey area for the spring 2004 cruise. Ship surveyed between 93°W and 90°W.

Fluorometry

Chlorophyll *a* concentrations were determined by fluorometric analysis using the Parsons et al. (1984) extraction method with a Turner Designs Model 10 fluorometer (excitation filter 440 nm and emission filter at 683 nm). The fluorometer was calibrated using a serial dilution (range: 0.1-0.01 mL stock) of a 100 µg/L chl-a primary standard (Sigma Chemical Co.). Samples for chlorophyll analysis were filtered onto Whatman GF/F glass fiber filters (25 mm diameter, nominal pore size of 0.7 µm) under <200 mm Hg vacuum and analyzed at sea. Filters were placed in glass test tubes containing 10 ml of 90% acetone and extracted for 24 hours at –20˚C in the dark. After extraction, samples were transferred to centrifuge tubes and centrifuged for 5 minutes to clarify the supernatant. The supernatant was transferred to glass culture tubes and fluorescence was measured. The presence of phaeopigments can lead to the overestimation of chlorophyll

a. Since initial fluorescence measurements include both chlorophyll *a* and pheopigments, approximately 0.3 ml (5 drops) of 5% HCl was added to the sample to convert chlorophylls to phaeopigments (Strickland et al. 1972). Fluorescence was re-measured and the difference between this and the initial measurement was used to obtain an estimate of total chlorophyll.

High Performance Liquid Chromatography

Photopigment analysis by High Performance Liquid Chromatography (HPLC) was based Photopigment Analysis Protocol adapted from Pinckney et al. (1996). Volumes filtered ranged from 200 mL to 3000 mL. Frozen filters (Whatman GF/F) were cut into slices and placed in 2 ml polypropylene microcentrifuge tubes. One ml of 100% acetone was added to each tube and the sample was sonicated using a Virtis VirSonic 100 for about 10 seconds at 3 Watts. The sample was kept in a beaker with ice to reduce evaporation and pigment degradation due to heating. Next, pigment was extracted by incubating the samples at –17˚C for 24 hours. Extract was filtered through a filter capsule (Gelman Acrodisc 13 CR PTFE, 0.45µm) and 350 to 750 µL of extract was injected into an amber glass autosampler vial. The Shimadzu HPLC draws 375 µL from the autosampler vial for injection into the chromatograph. The total final volume in the vial is usually 2-3 times the injection volume (at least 750 µL). However, lower extracted volumes are acceptable if the extracted volume plus the volume of ammonium acetate is higher than 375 µL. Ammonium acetate (1M; ratio 1.25, extract:ammonium acetate) was added to the extract as an ion-pairing (IP) solution just prior to placing the vial into the autosampler. An ion-pairing solution prevents pigment degradation within

12 hours of addition. The vial was placed in the HPLC cooling rack for analysis. Photopigment concentrations were determined by HPLC using a Shimadzu HPLC and compared to results obtained from fluorometry. The Shimadzu HPLC is equipped with a monomeric (Rainin Microsorb-MV, 0.46 x 10 cm, 3 mm) and a polymeric (Vydac 201TP, 0.46 x 25 cm, 5 mm) reverse-phase C_{18} column in series. The monomeric column provides strong retention while the polymeric column optimizes pigment separation by selecting for similar compounds with minor differences in molecular structure and shape (Van Heukelem et al. 1994; Jeffrey et al. 1997). Pigment peaks were identified by comparison of retention times and absorption spectra with pure crystalline standards, including chlorophylls *a*, *b*, ß-carotene (Sigma Chemical Company), lutein, canthaxanthin, echinenone, and zeaxanthin (Hoffman-LaRoche and Company).

Data Analysis

Density calculation and analysis: Density was calculated for both discrete and continuous data using the Equation of State (Knauss 1996):

$$\rho - \rho_o = [- \bar{a} (T - T_o) + \bar{b} (S - S_o) + \bar{k} p] \qquad (2)$$

where ρ is density, ρ_o = 1027 kg/m^3, T = temperature, T_o = 10°C, S = salinity, S_o = 35 psu, $\bar{a}$ = 0.15 kg/m^3 per degree C, $\bar{b}$ = 0.78 kg/m^3 per part per thousand salinity, $\bar{k}$ = 4.5 x 10^{-3} kg/m^3 per decibar. Results were converted to σ_t by subtracting 1000.

Frontal zones were identified by locating data intervals where σ_t changed by 1.5 points over a distance of 1 km. These fronts were visually compared to satellite images

of sea surface temperature (SST) for corresponding dates (each image is a 3-day composite, see Appendix B). All satellite images were obtained from Johns Hopkins University's Applied Physics Laboratory Ocean Remote Sensing website (June 2004). Density fronts identified using the above criteria were visually compared with temperature fronts. Only those points where density fronts coincided with visible temperature fronts were selected as frontal zones for this study (see Figures 5-8). Since density is a function of temperature and salinity, density fronts could have been compared to both temperature and salinity fronts. However, the range of salinities across fronts did not vary more than a tenth of a degree, while salinity varied from 1 to 4 degrees. Once identified, each frontal zone was divided into three locations--before front, front, and after front—to distinguish between the front itself and the two converging water masses. The two to three data points encompassing the change in density were considered the "front" location. The ten data points before the "front" were considered the "before front" location. Finally, the ten data points after the "front" were considered the "after front" location.

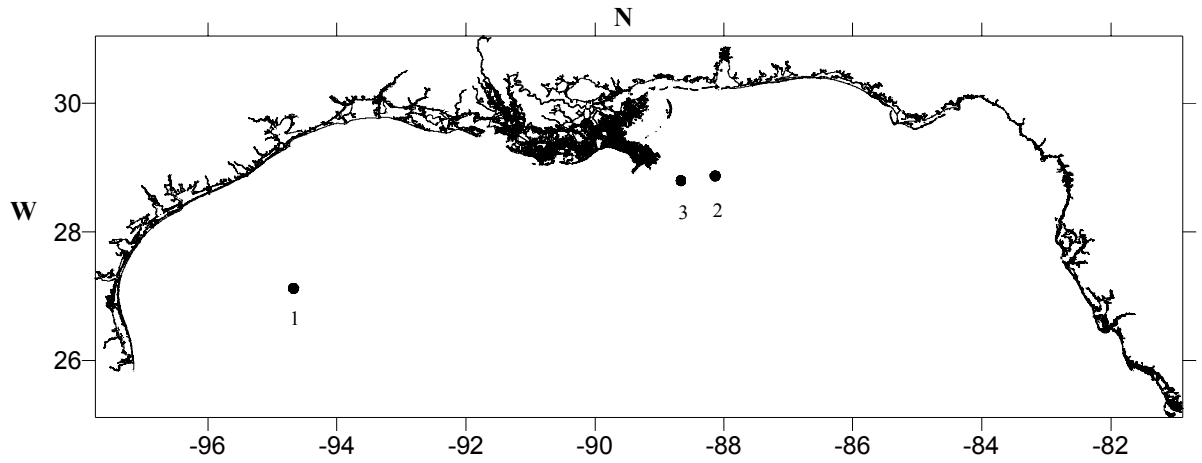

Figure 5. Location of fronts for summer 2002. Front locations were identified by cross-referencing changes in σ_t with changes in SST based on satellite imagery (see Appendix B). Fronts are numbered in order of occurrence along ship's track.

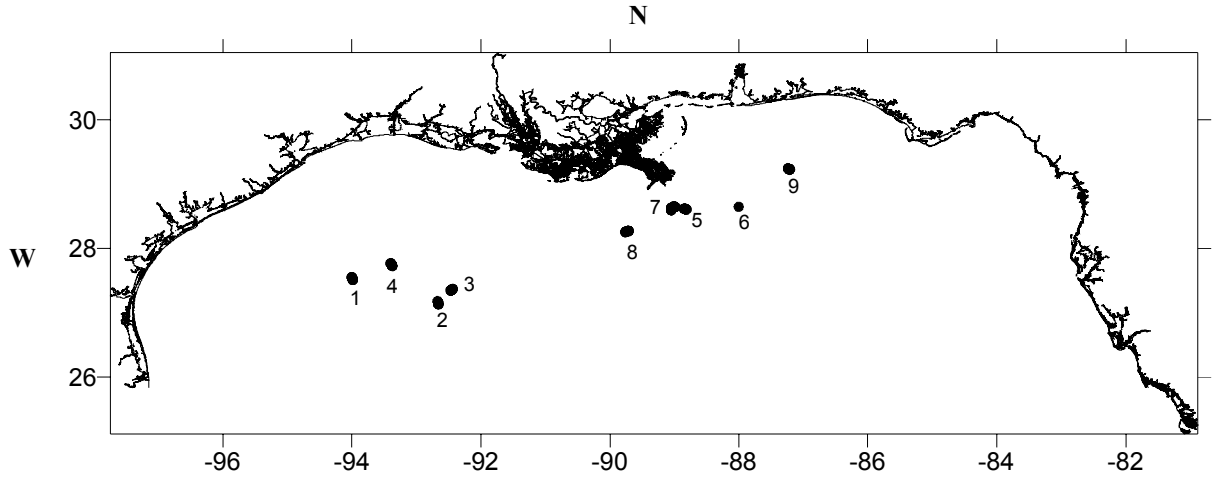

Figure 6. Location of fronts for summer 2003. Front locations were identified by cross- referencing changes in σ_t with changes in SST based on satellite imagery (see Appendix B). Fronts are numbered in order of occurrence along ship's track.

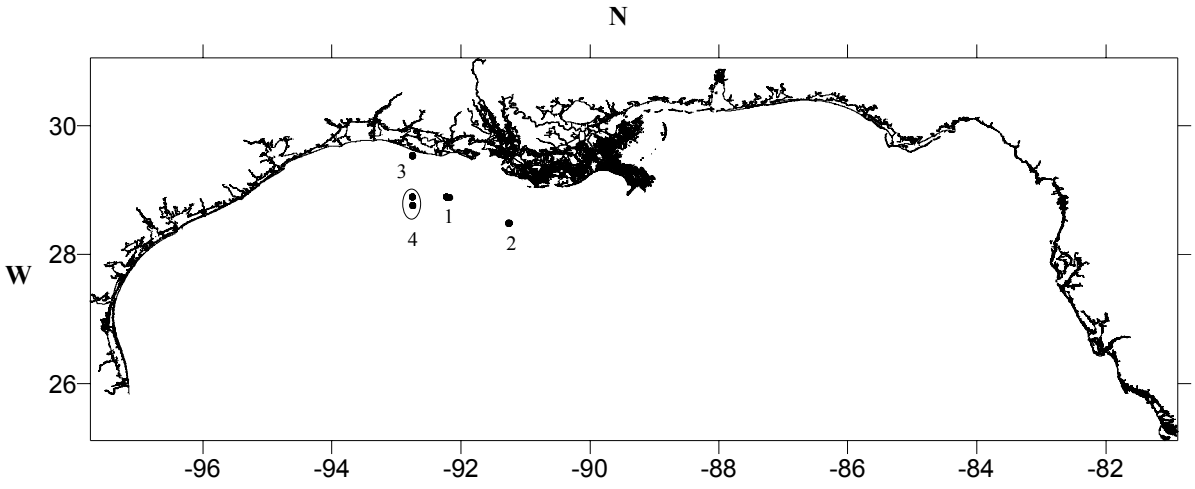

Figure 7. Location of fronts for fall 2003. Circle indicates the range of a front. Front locations were identified by cross-referencing changes in σ_t with changes in SST based on satellite imagery (see Appendix B). Fronts are numbered in order of occurrence along ship's track.

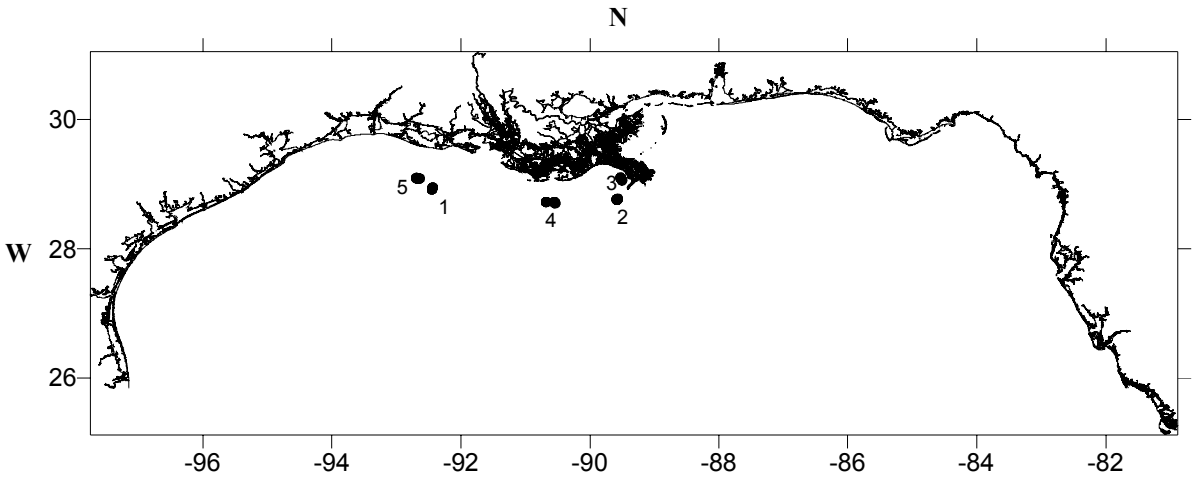

Figure 8. Location of fronts for spring 2004. Front locations were identified by cross-referencing changes in σ_t with changes in SST based on satellite imagery (see Appendix B). Fronts are numbered in order of occurrence along ship's track.

Chlorophyll *a* calculation and analysis: Chl *a* concentrations were determined by both fluorometry and HPLC from water samples collected at each station along each cruise track. Since fluorescence per chlorophyll varies, these discrete measurements of chlorophyll *a* were used to calibrate continuous fluorescence measurements made by an onboard flow-through fluorometer. Chl *a* concentrations for continuous data were calculated using a linear regression of fluorescence (voltage) v. chlorophyll *a* (μg/L). Fluorescence values used in the linear regression were obtained from continuous *in vivo* fluorescence measurements recorded by a Turner Designs fluorometer for each sampling station. Chl *a* values used in the linear regression for the 2002 & 2003 summer cruises were the result of fluorometric analysis of samples from each station. Chl *a* values used in the linear regression for the fall 2003 and spring 2004 cruises were the result of HPLC analysis of samples from each station. The resulting equation was used to define a calibration curve for the data collected on each cruise. The equation defined for each cruise was then used to calculate chl *a* concentrations for continuous data using known fluorescence measurements. The equations used are as follows:

Summer 2002 $$CHL = 0.0032048 * Fluor - 0.355 \quad (3)$$

Summer 2003 $$CHL = 0.005777 * High\ Fluor - 0.679 \quad (4)$$

$$CHL = 0.0023105 * Low\ Fluor - 0.131 \quad (5)$$

Fall 2003 $CHL = 0.0006 * Fluor + 0.008$ (6)

Spring 2004 $CHL = 0.0033 * Fluor$ (7)

where CHL is chlorophyll *a*, fluor = fluorescence, high fluor = fluorescence > 200 (voltage), and low fluor = fluorescence < 200 (voltage).

Continuous algal group abundance calculation and analysis: Algal group abundance for continuous data was calculated by interpolation. Percent concentration of each algal group measured at each sampling station was inserted into continuous data according to date and time. Adjacent percentages (discrete samples) for each algal group were averaged, converted to fractions (divided by 100), and multiplied by chl *a* concentrations calculated for each continuous interval using equations 3 through 7. All diversity values were calculated using the Shannon-Weaver Index (Eq. 1).

Statistics: All statistical analysis was completed using SPSS 12.0. All tests of normality were conducted using K-S Normality tests. All homogeneity of variance tests were carried out using Levene's test for homogeneity. The data at and between frontal zones did not exhibit normal distributions or homogeneous variances, therefore non-parametric Kruskal-Wallis and Dunnett's T3 Tests were used to identify any significant differences in chl *a* concentrations and algal group abundances among different locations within a frontal zone and between frontal zones. The Kruskal-Wallis test, a nonparametric equivalent of the one-way analysis of variance which does not make any assumptions about homogeneity of variances or normal distribution, was completed for

each front. This test addresses the null hypothesis that the samples from each location (before front, front, and after front) have the same median value.

If the Kruskal-Wallis test identified a significant difference between the medians at each location within a front, then a Dunnett's T3 test was used to provide *post hoc* results. Like the Kruskal-Wallis test, the Dunnett's T3 test makes no assumptions about homogeneity of variances and normal distributions. A Dunnett's T3 test can be used to conduct pairwise multiple comparisons which identify significant differences between the means of each level within a factor. In this study, the Dunnett's T3 pairwise multiple comparison test was used to compare locations within each front (before front, front, and after front) as well as to compare each front with the other.

RESULTS

This section describes the physical property distributions--temperature, salinity, and density—found in the study area during each of 4 cruises. A general overview of phytoplankton biomass and community structure during each cruise is provided. This overview is followed by a review of the total number of fronts found during each cruise. Finally, the results of statistical analyses comparing the biomass and community structure between fronts and adjacent water masses, and between the fronts themselves are presented.

Temperature

Sea surface temperature (SST) values showed a higher range during the fall 2003 and spring 2004 cruises than it did during the summer cruises. During summer 2002, surface temperature ranged from 27.9°C to 31.0°C throughout the entire study area. SST during the summer 2003 cruise was very similar, with a low of 26.7°C and a high of 31.3°C. There was a much higher range in SST values during the Fall 2003 cruise, with a low of 23.4°C and a high of 30.9°C. During the Spring 2004 cruise, the lowest temperature was 17.7°C and the highest was 31°C. Average temperature across fronts are illustrated in Figure 9. Highest average temperature changes between locations were found during summer 2002.

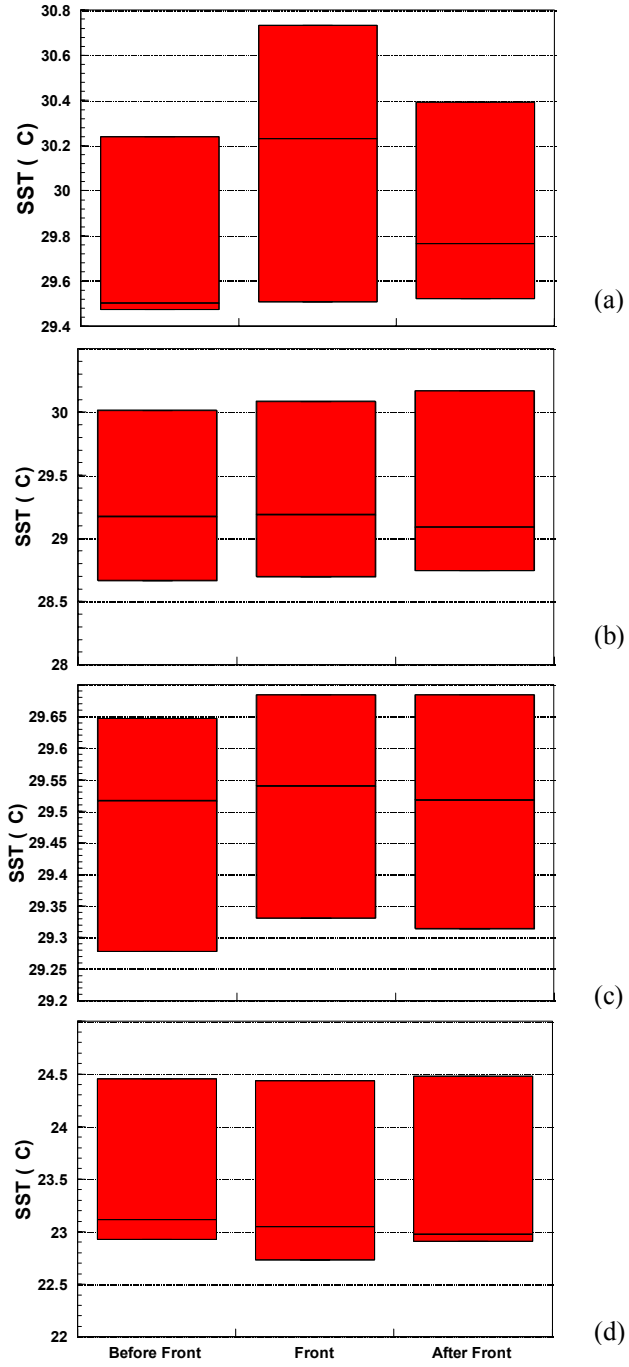

Figure 9. Boxplots showing average SST at before front, front, and after front locations during (a) summer 2002, (b) summer 2003, (c) fall 2003, and (d) spring 2004. Box whiskers are too small to be distinguished.

Salinity

Salinity in the northern GOM is mainly influenced by freshwater input from the Mississippi and Atchafalaya Rivers. Continuous salinity measurements generally showed a strong freshwater influence nearshore for all cruises and an increase in salinity with distance offshore. During the summer 2003 cruise, lower salinities were found farther offshore than during the summer 2002 cruise. This could be due to tropical storms which passed through the area just before and during the summer 2003 cruise depositing large amounts of fresh, low salinity water. Average salinity across fronts was highest during summer 2003 and lowest during fall 2003 (see Figure 10).

Density

The continuous density values calculated using the Equation of State generally followed salinity measurements. Highest densities were found offshore in higher salinity water and lower densities were found nearer to the coast in lower salinity waters. A pocket of lower density water was seen in the southeast corner of the study area during the summer 2002 and 2003 cruises, possibly associated with anti-cyclonic eddies. Like salinity, the lower density field extended farther south during the summer 2003 cruise. Average density across fronts was highest during summer 2003 and lowest during fall 2003. The greatest difference in average density between front locations was found during summer 2002 (See Figure 11).

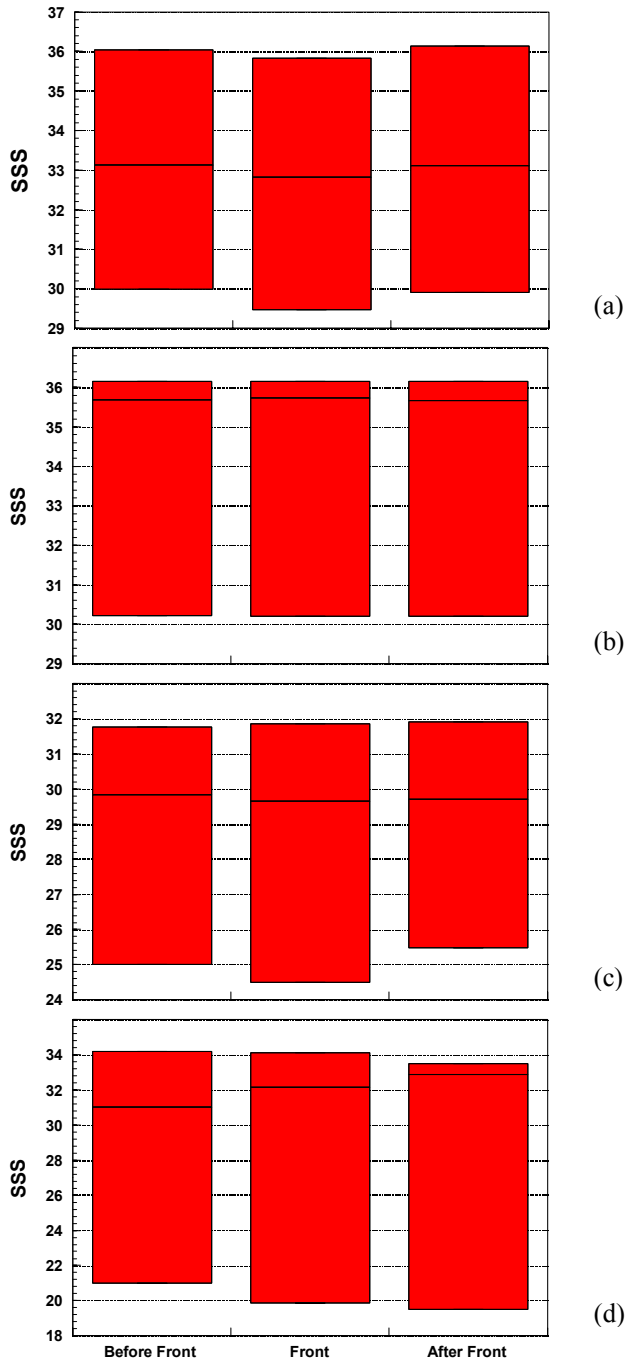

Figure 10. Boxplots showing average sea surface salinity at before front, front, and after front locations during the (a) summer 2002, (b) summer 2003, (c) fall 2003, and (d) spring 2004. Box whiskers are too small to be distinguished.

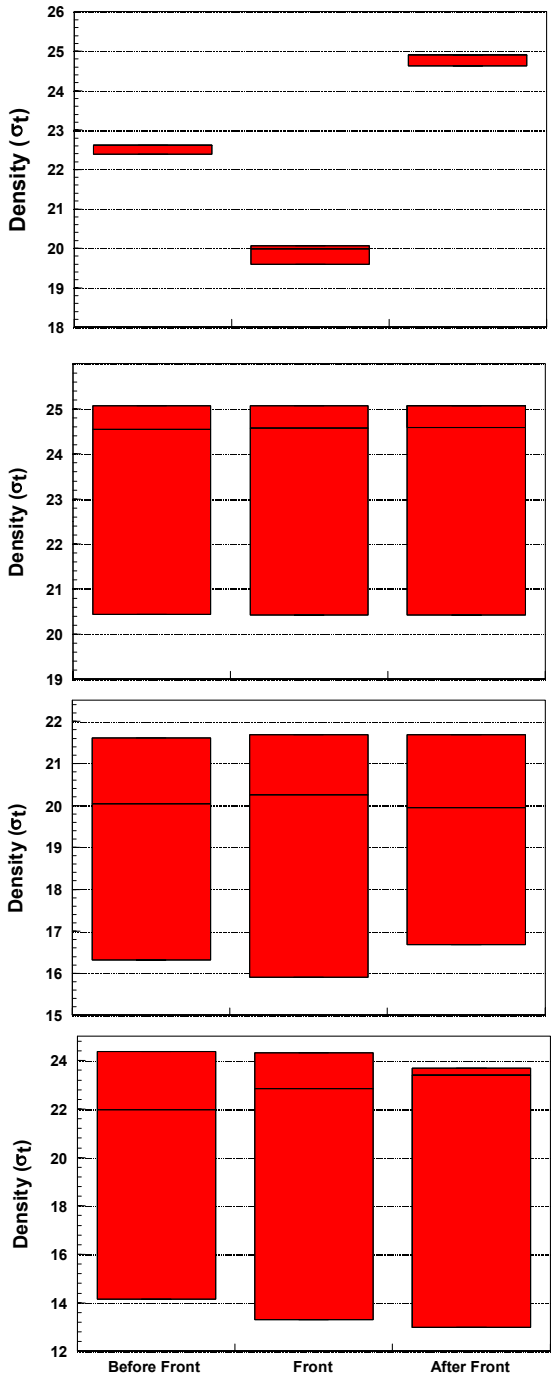

Figure 11. Boxplots showing average sea surface density at before front, front, and after front locations during (a) summer 2002, (b) summer 2003, (c) fall 2003, (d) spring 2004. Box whiskers are too small to be distinguished.

Phytoplankton Biomass and Community Structure

Total chlorophyll *a* concentrations for the summer 2002 cruise (measured as chl *a* per volume) ranged from 0.01 µg/L to 1.33 µg/L. Of the total chl *a* measured for each station, the highest percentage belonged to cyanobacteria (69.5%). Chrysophytes were the next most abundant (21.2%) and prasinophytes were the least abundant 0.2%). During the summer 2003 cruise, prasinophytes, cryptophytes, and haptophytes were not found. The total chl *a* biomass ranged from 0.13 µg/L to 11.7 µg/L. The largest percentage of chl *a* was made up of cyanobacteria (69.9%). Diatoms were the next most abundant (14.3%) and prasinophytes were absent or in very low concentrations at all stations. During the fall 2003 cruise, the total chl *a* biomass ranged from 0.01 µg/L to 0.40 µg/L. Chlorophytes were the most dominant algal group, making up 74.0% of the total chl *a* concentration. Cyanobacteria followed at 17% of the total chl *a* concentration, while dinoflagellates were the least abundant (0.4%). Dinoflagellates were only present in 2 samples collected just nearshore along the eastern Texas coast. During the spring 2004 cruise, the total chl *a* biomass ranged from 0.04 µg/L to 4.16 µg/L diatoms were the most abundant algal group (44.5%), followed by chlorophytes (16.1%). Prasinophytes (4.8%) and dinoflagellates (6.8%), were the least abundant.

Raw data for chl *a* and algal group concentrations are shown in Appendix A. Below (Fig. 12) is a column chart which illustrates average concentrations of chl *a* and algal groups during each of the four cruises.

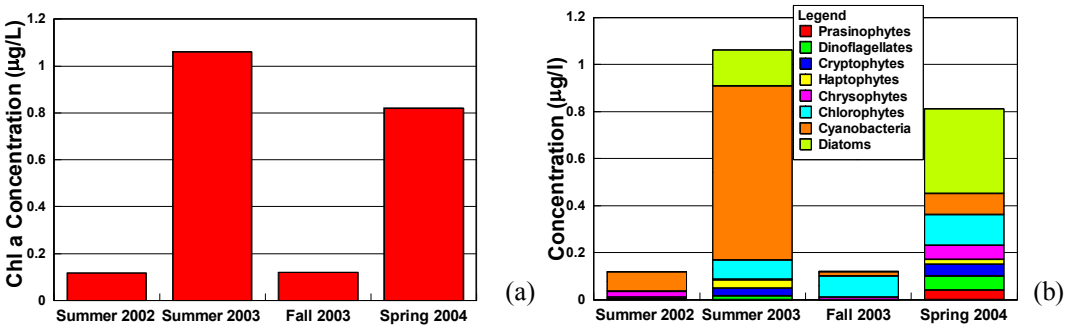

Figure 12. Column charts showing (a) mean concentrations of chl *a* and (b) mean algal group concentration for each of the four cruises studied.

Fronts

A total of 2,823 data intervals were identified during all four cruises where σ_t changed by 1.5 points over 1 km: 47 during summer 2002, 1,604 during summer 2003, 44 during fall 2003, and 1,128 during spring 2004. After resolution of the data points to a scale of 1556 km x 2000 km (18°N-32°N, 80°W-98°W), which was the scale of the satellite images to which they were being compared, most data points were found to be concentrated in clusters. Approximately 7 clusters were found during summer 2002, 10 during summer 2003, 5 during fall 2003, and 7 during spring 2004. Visual comparison of these clusters with satellite images resulted in the identification of a total of 21 fronts encountered during sampling: 3 during summer 2002, 9 during summer 2003, 4 during fall 2003, and 5 during spring 2004. Figures 5-8 show the location of each front within the GOM, while Appendix B shows each front in relation to its corresponding temperature front. Average distance between before front, front, and after front locations are listed in Table 5.

Table 5. Average distances (km) between before front, front, and after front locations.

Location	Summer 2002	Summer 2003	Fall 2003	Spring 2004
Before Front:Front	0.12	0.17	0.05	0.16
Front:After Front	0.11	0.18	0.06	0.18

Comparison of phytoplankton biomass and algal group abundance within fronts: Chl *a* and algal group concentration showed limited differences between before front, front, and after front locations (see Figure 13-16). Of the three fronts encountered during summer 2002 (see Figure 13-16), only front 2 showed a significant difference in both chl *a* and algal group concentration between any two locations. A significant difference (see Appendix A) existed at the before front and after front (BF:AF) location pair for all chl *a* and all pigments. Chl *a* and all algal group concentrations were significantly higher inside front 2 than in the water masses immediately before the front. Prasinophytes were absent at fronts 2 and 3.

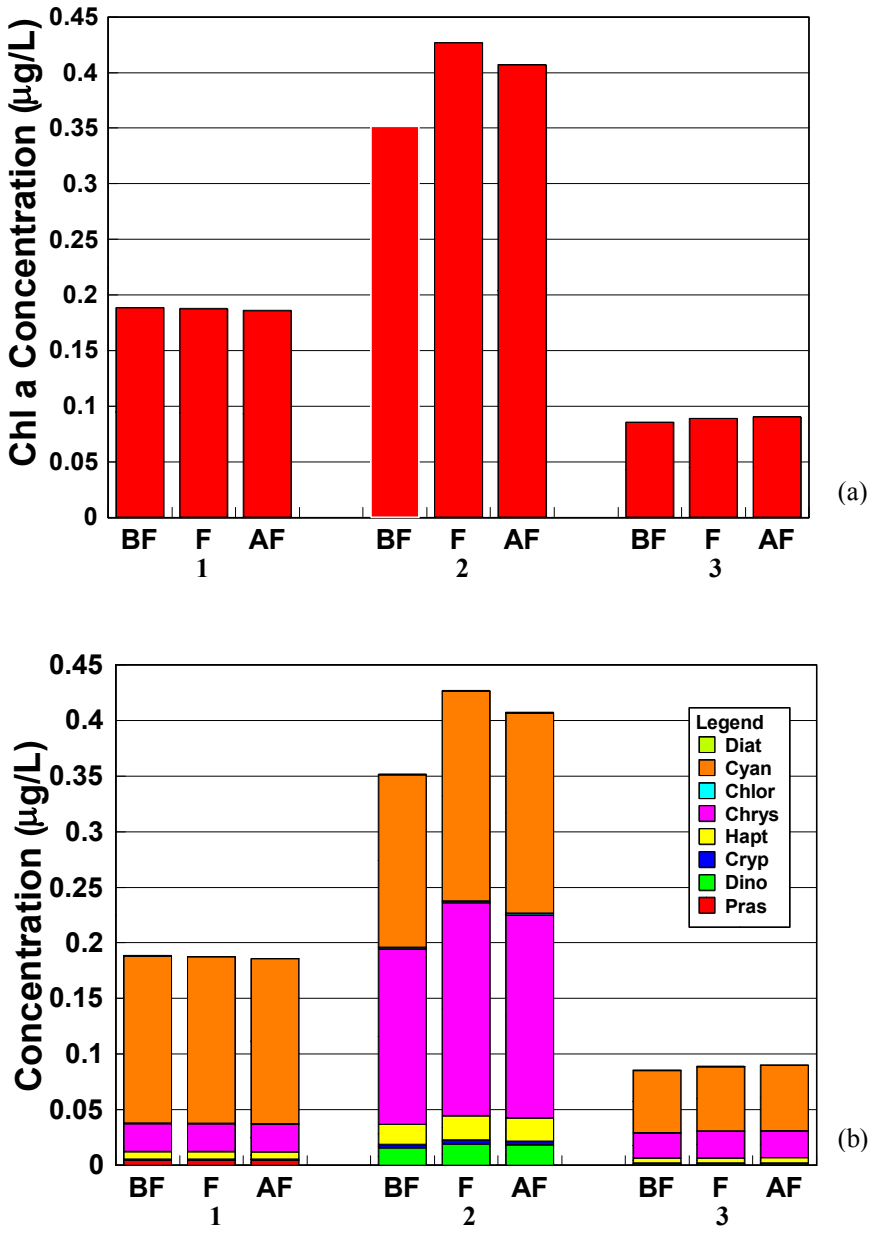

Figure 13. Column charts showing (a) the concentrations (µg/L) of chl *a* and (b) algal group concentrations for each front during the summer 2002 cruise. BF = before front location, F = within front location, AF = after front location.

During the summer of 2003 (see Figure 14), there was a significant difference in haptophyte and chrysophyte concentration between the front and both adjacent water masses (BF:F and F:AF pairs) at front 6. However, the concentration within the front was lower than in either of the adjacent water masses. Significant differences in the concentration of chl *a* and algal groups between water masses on either side of a front (BF:AF pair) were found at several fronts: chl *a* – front 5; dinoflagellates – fronts 2 and 6; cryptophytes – fronts 2, 5, and 8; haptophytes – fronts 2, 5, and 8; chrysophytes – fronts 2, 5, 6, and 8; chlorophytes – front 9; cyanobacteria – fronts 5 and 9; diatoms – fronts 5, 6, 8, and 9. Chrysophytes were absent at front 8.

Four fronts were identified during the fall 2003 cruise (see Figure 15). Chl *a* concentration was significantly different between the F:AF pair and the BF:AF pair. The highest concentration occurred in the AF location. The concentration of dinoflagellates, chrysophytes, and chlorophytes at front 3 were significantly higher only

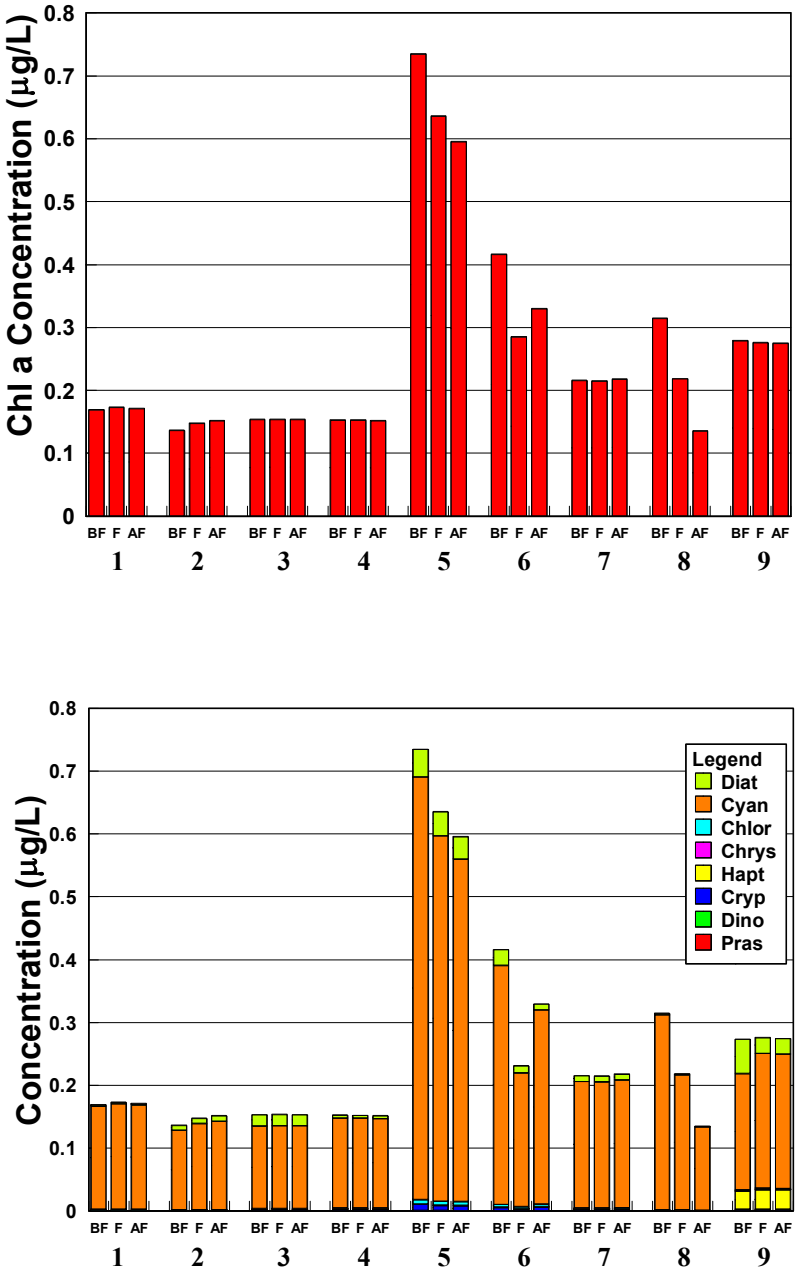

Figure 14. Column charts showing (a) the concentrations (µg/L) of chl *a* and (b) algal group concentrations for each front during the summer 2003 cruise. BF = before front location, F = within front location, AF = after front location.

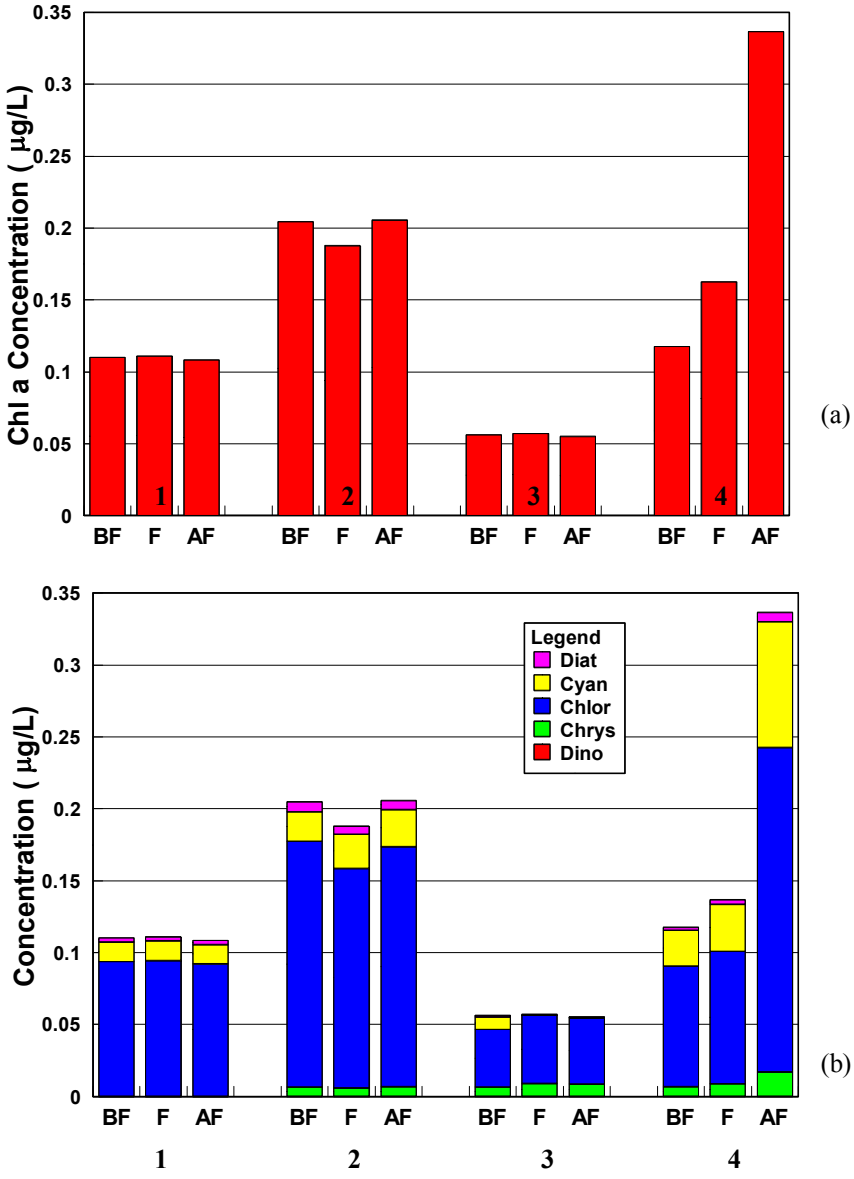

Figure 15. Column charts showing (a) the concentrations (µg/L) of chl *a* and (b) algal group concentrations for each front during the fall 2003 cruise. BF = before front location, F = within front location, AF = after front location.

between the BF:F pairs. In all three cases (dinoflagellates, chrysophytes, and chlorophytes), concentrations were significantly different in the water masses on either side of the front (BF:AF pairs). Cyanobacteria and diatom concentration were significantly different between locations at the BF:F pair and the BF:AF pair. In both cases, the concentration before the front was the highest of the three locations. Dinoflagellates were completely absent at fronts 1, 2, and 4.

During the spring 2004 cruise (see Figure 16), chl *a* and all algal group concentration exhibited a significant difference at the BF:AF location pairs at front 5. Likewise, chl *a* and all algal group concentrations were significantly different at the F:AF location pair at front 3.

Comparison of phytoplankton biomass and algal group abundance between fronts: Both chl *a* and algal group concentrations for all groups were significantly different between fronts during summer 2002 (see Appendix A). The highest chlorophyll *a* concentration (0.39μg/L – 0.48 μg/L) was found at front 2. The most abundant algal group at front 1 was cyanobacteria (0.15 μg/L), the least abundant were diatoms (2.32×10^{-7} μg/L). At front 2, the most abundant group were both chrysophytes (0.16 μg/L – 0.19 μg/L) and cyanobacteria (0.16 μg/L – 0.19 μg/L) and the least

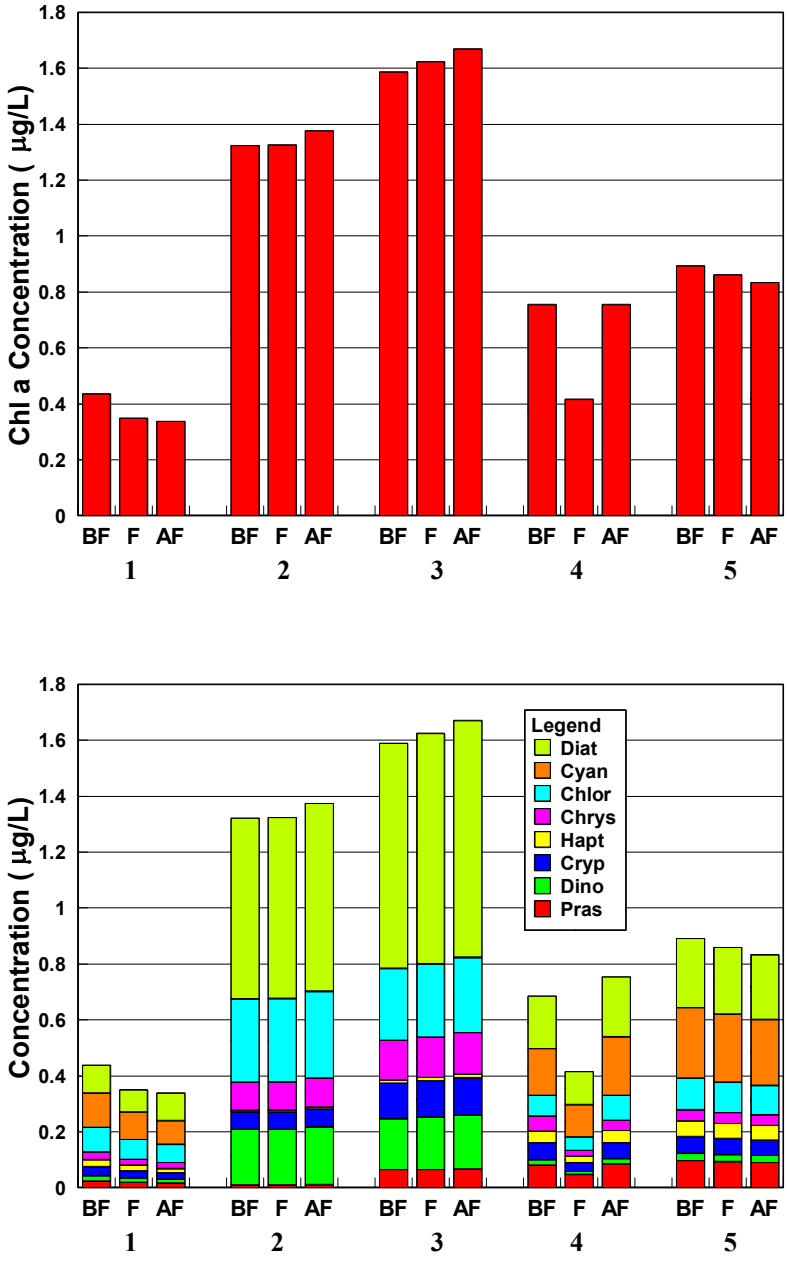

Figure 16. Column charts showing (a) the concentrations (µg/L) of chl *a* and (b) algal group concentrations for each front during the spring 2004 cruise. BF = before front location, F = within front location, AF = after front location.

abundant were prasinophytes (1.19×10^{-18} µg/L 31.45×10^{-18} µg/L). Cyanobacteria (5.59×10^{-2} – 5.90×10^{-2} µg/L) were the most abundant group at front 3 and prasinophytes (1.04×10^{-18} µg/L – 1.10×10^{-18} µg/L) were the least abundant.

Chl *a* and all algal group concentrations during the summer 2003 cruise were significantly different between fronts at all of the front pairs except the following (see Appendix A): Chl *a* – 1:8, 2:3, 2:4, 3:4, 4:8, 7:8; dinoflagellates – 1:9, 2:9, 4:9, 8:9; cryptophytes – 4:9, 6:9; haptophytes – 3:8; chrysophytes – 3:8; chlorophytes – 4:9, 7:9; cyanobacteria – 1:8, 2:3, 2:4, 7:8, 7:9, 8:9; diatoms – 3:6, 5:9. Chl *a* concentrations (see Table 6) were highest at front 5 (0.64 µg/L-0.74 µg/L). Cyanobacteria were the most abundant group at all fronts, while prasinophytes were very low or completely absent at all fronts.

A statistical difference existed between chl *a* and all algal group concentrations during fall 2003 at all front pairs except the following (see Appendix A): chl *a* – 1:3, 2:4; dinoflagellates – 1:4, 2:4, chlorophytes – 2:4; diatoms – 1:4. The highest chlorophyll *a* concentration was found at front 2 (0.189 µg/L – 0.21 µg/L). Chlorophytes were the most abundant algal group at all fronts. Dinoflagellates were very low or absent at all fronts.

Chl *a* and all algal group concentrations during the spring 2004 cruise were significantly different between fronts at all of the front pairs except the following (see Appendix A): dinoflagellates – 1:4; cryptophytes – 2:4; chrysophytes – 4:5; and chlorophytes – 1:4. The highest chlorophyll *a* concentration was found at front 3 (1.58

μg/L – 1.7 μg/L). Diatoms were the most abundant algal group at fronts 2 and 3. Cyanobacteria were the most abundant algal group at fronts 1, 4, and 5.

Diversity

Diversity values are typically low, between 1 and 2.5, in coastal waters and highest, between 3.5 and 5, in oceanic waters (Margalef 1978). All of the diversity values found during the 4 cruises studied were between 0 and 2.6, values characteristic of low diversity environments. During summer 2002 and 2003, or spring 2004, no significant differences in diversity were found between before front, front, and after front for any of the frontal zones identified (See Figs. 17-20). Diversity values calculated were the very similar or identical for all 3 defined locations for all fronts during these three cruises. A significant difference did exist at front 3 of the fall 2003 cruise. Diversity at this front was significantly different (see Appendix A) between the BF:F and BF:AF pairs. Diversity values between fronts were significantly different between all fronts during the summer 2002 (see Appendix A) and spring 2004 (see Appendix A). During summer 2003, diversity values were significantly different between all fronts except 5 and 6 (see Appendix A). During fall 2003, diversity values were significantly difference between all fronts except 2 and 3 (see Appendix A).

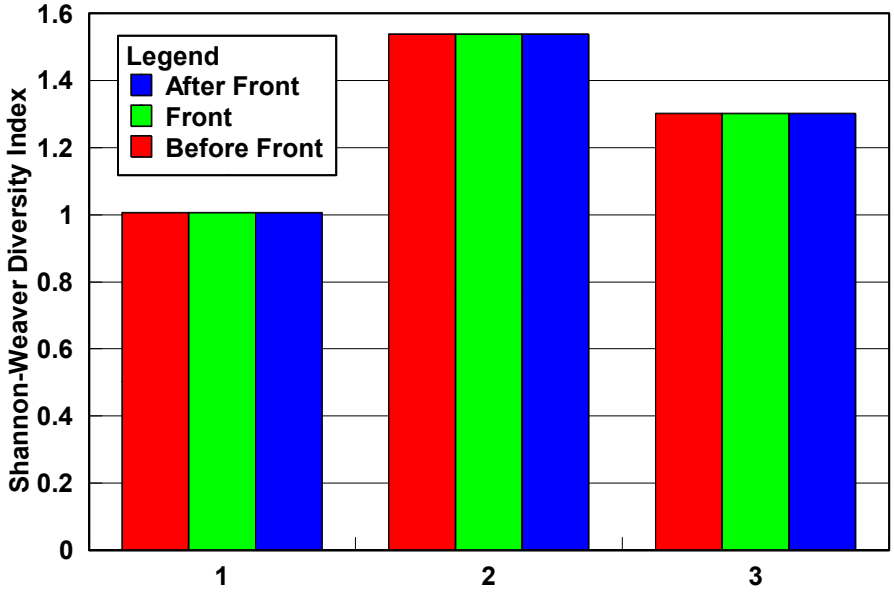

Figure 17. Column chart showing diversity values for before front, front, and after front locations during the summer 2002 cruise.

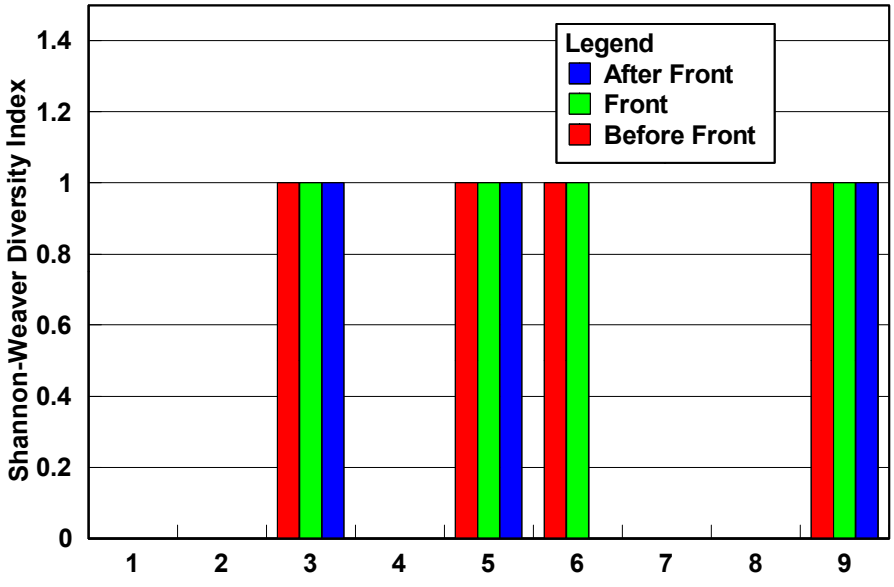

Figure 18. Column chart showing diversity values for before front, front, and after front locations during the summer 2003 cruise.

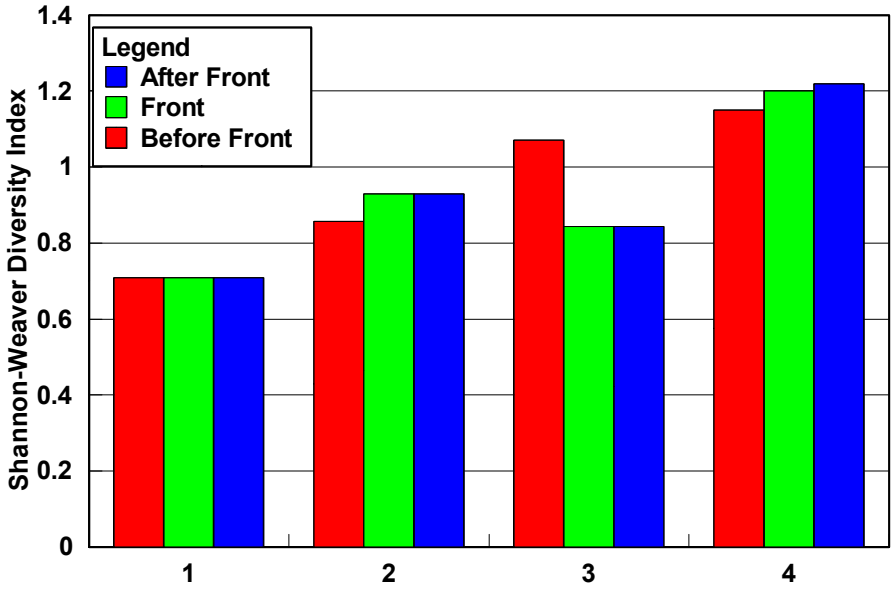

Figure 19. Column chart showing diversity values for before front, front, and after front locations during the fall 2003 cruise.

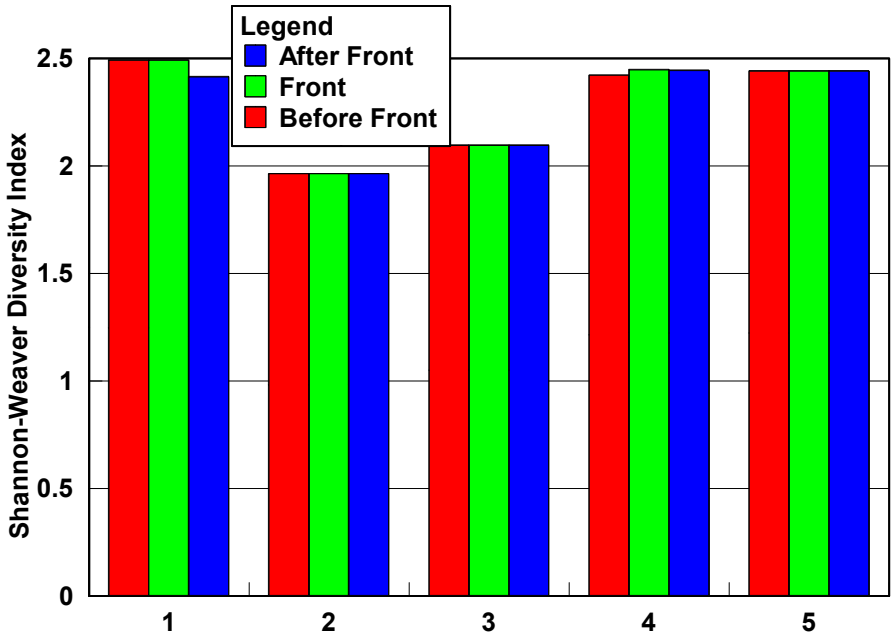

Figure 20. Column chart showing diversity values for before front, front, and after front locations during the spring 2004 cruise.

During the summer 2002 cruise, diversity was highest at front 2 (1.5) and lowest at front 1 (1.0). During the summer 2003 cruise, diversity values ranged from 0 at fronts 1, 2, 4, 8, and 9 to 1 at fronts 3, 6, and 10. Diversity values during the fall 2003 cruise were highest at front 4 (1.2) and lowest at front 1 (0.71). During the spring 2004 cruise, diversity was highest at front 1 (2.5) and lowest at front 2 (2.0).

DISCUSSION

Phytoplankton Biomass and Community Structure at Frontal Zones

Both phytoplankton biomass and community structure exhibited very little difference between front locations. Total phytoplankton biomass, measured as µg chl *a*/L, was not significantly higher within fronts than outside of fronts. Although total chl *a* concentrations were significantly different between locations (before front, within front, and after front) at some fronts, the concentration of total chl *a* was not necessarily higher within the front than in adjacent waters. When total chl *a* concentration was higher within the front (summer 2002-front 2, summer 2003-front 1, fall 2003-fronts 1 and 3) the difference between concentrations at the three locations were not statistically significant.

Previous studies of biomass at frontal zones have demonstrated a clear association between frontal zones and enhanced phytoplankton biomass (Laubscher et al. 1993; Flint et al. 2002; Kopczyńska et al. 2003). Among others, Dustan and Pinckney (1989) and Pinckney and Dustan (1990) have shown increased phytoplankton biomass at tidal fronts in Charleston Harbor. Jones et al. (1981) showed that an increase in phytoplankton concentration occurs at wind-driven fronts and Simpson et al. (1982) showed an increase in biomass at topographic fronts.

Community structure, measured as individual algal group concentrations (µg chl *a*/L), also showed limited differences between frontal locations. No fronts exhibited differences between the front and both adjacent water masses. Differences in

concentrations between the front and one adjacent water mass (BF:F or F:AF pair) and between the water masses on either side of the front (BF:AF pair) were more common. Likewise, community structure measured as diversity varied very little between locations within fronts. There was no significant difference in diversity values between before front, front, and after front at any front during summer 2002, summer 2003, or spring 2004. Only the BF:F and BF:AF pairs at front 3 during fall 2003 exhibited a significant diversity difference.

Previous studies of phytoplankton algal group abundance in frontal zones have demonstrated that community structure within fronts is different compared with adjacent water masses (Pingree et al 1975; Flint et al. 2002; Kopczyńska et al. 2003). These studies show that fronts are typically dominated by one or a few algal groups. A shift in community structure from relatively even abundances of individual algal groups to dominance by one group would be reflected in diversity values. Diversity would be lower inside the front than in the adjacent water masses. My study found no differences in diversity across fronts.

Phytoplankton Biomass and Community Structure Between Frontal Zones

Within the GOM, studies have examined the distribution of phytoplankton in relation to circulation, riverine input and nutrient content but not in relation to fronts. For example, Qian et al. (2003) used HPLC analysis to study both the total chl *a* and the algal group abundance in the northeast GOM, concluding that near-surface and sub-surface waters near the Mississippi-Mobile Bay outflow regions had the highest chl *a* concentrations during the 3 years of the study. They also concluded that phytoplankton

biomass in the NEGOM study area was largely controlled by proximity to, magnitude, and timing of the freshwater outflows from rivers, bays, and estuaries and that community structure was controlled largely by variations in salinity (river input), nutrients, season, and light conditions. Belabbassi (2001) measured chlorophyll *a* concentration in the NEGOM area in relation to physical processes and also found that high concentrations were related to riverine input. Chlorophyll *a* biomass in this study was found to be 2-3 times greater within the Mississippi River plume than outside of it. Al-Abdulkader (1996) conducted an ecological study of phytoplankton along the Texas-Louisina coast and found that the inner shelf was much more productive than the outer shelf.

Phytoplankton biomass distributions between fronts during the 4 cruises studied did not show a consistent relationship between chlorophyll *a* or algal group concentration and proximity to high-nutrient freshwater output. One exception was summer 2003. Chl *a* concentration at these 5 fronts where significantly higher at the nearshore fronts, with the exception of front pairs 3:8 and 4:8.

Diversity

Diversity indices, such as the Shannon-Weaver Index are designed to describe the structure of a community of organisms based on the number of species present as well as the number of individuals of each species. In this study, diversity was calculated using algal group concentration (derived from CHEMTAX) instead of numbers of individuals. No differences in diversity were found across fronts during any of the four

cruises studied. Diversity between fronts was significantly different between all but 2 frontal pairs.

Diversity indices are usually calculated using a large number of species, while the highest number of algal groups found during any one cruise in this study was 8. The Shannon-Weaver Index at some frontal locations equaled zero. These results indicate that diversity values calculated using a small number of algal groups, which are general categories of phytoplankton and could represent a many different species, are not comparable to values calculated using a large number of species. The diversity values calculated can, however, provide information about relative species diversity between locations and between fronts.

Identification of Fronts

Temperature has been used by several previous studies to track the position of frontal zones (Lutjeharms and Valentine 1984; Lutjeharms and Foldvik 1986; Laubscher et al. 1993; Flint et al. 2002). Flint's group identified fronts across 5 transects in the Bering Sea using a CTD, while Laubscher et al. (1993) used both sharp changes in temperature (measured by direct water sampling) and nutrients to establish the limits of frontal zones. More recently, satellite images of SST have been used to locate fronts (Kostianoy et al. 2004; Royer et al. 2004; Stegmann et al. 2004) . Etnoyer et al. (2004) recently used satellite SST data (Miami MCSST) together with edge-detection software (slope functions that identify the highest rate of change in temperature across a surface) to determine the position and extent of frontal regions in the Pacific from the Bering Sea to Baja California. They specifically looked for areas where the features persisted for 9

months or more and found that these areas accounted for less than 1% of the study area and were concentrated in the region known as the Baja California Frontal System (BCFS). Hu et al. (2003) compared ship and satellite bio-optical measurements of SST in the northeast GOM. They found that the mean error between the two measurements was less than ±0.5°C regardless of time difference. High discrepancies (±1°C) found on some cruises were attributed to high river inputs.

In this study, fronts were identified using both density values calculated using the equation of state and visible SST fronts. Density is a function of both temperature and salinity. However, in offshore waters of the GOM, surface water salinity changes very little. Whereas, temperature can exhibit greater changes over short spatial scales. Since the average distance between before front, front, and after front locations in this study was less than 1 km (see Table 5), density fronts were only compared to SST.

Remote Sensing and Community Structure

Satellite images have increasingly been used to estimate chlorophyll concentration over large areas (Muller-Karger et al. 1991; Hu et al. 2003; Stegmann et al. 2004). Müller-Karger et al. (1991) used multiyear series of coastal zone color scanner (CZCS) and advanced very high resolution radiometer (AVHRR) images to derive monthly climatologies of near-surface pigment concentration and sea-surface temperature. Satellite (SeaWiFS) images of chlorophyll concentration (mg m^{-3}) were used as a part of NEGOM and compared with continuous *in vivo* fluorescence measurements calibrated with extracted chlorophyll concentrations. At low concentrations, mean relative error was within ± 35% SeaWiFS specifications. At high

concentrations, the mean relative error reached >50% before correction with a MODIS bio-optical algorithm which distinguishes CDOM from chlorophyll, and was lowered to <39% after correction (Hu et al. 2003).

Although satellite images have been shown to provide reliable estimates of chl *a* concentrations, these images do not provide any information regarding the algal groups represented by sea color images. Several methods, including cell counts, fluorometry, HPLC, and flow cytometry have been used in the past to determine both biomass and community structure of phytoplankton (Laubscher et al. 1993; Mackey et al. 1998; Fiala et al. 2003; Kopczyńska et al. 2003). Unlike satellite imagery, these methods are limited geographically in that they can only be used to analyze data collected at sampling sites. My study proposes that a combination of the large scale data provided by satellite imaging and the smaller scale data provided by ship sampling methods can provide a better understanding of changes in phytoplankton biomass and community structure over large areas such as the GOM.

A possible limitation for the use of satellite ocean color estimates of chl *a* concentrations with data derived from shipboard measurements is the time lag between satellite and field measurements (Hu et al. 2003). Satellite data are averaged over multiple days to improve the spatial coverage (remove cloud cover) and reduce noise. Thus, ship and satellite data in some areas could be several days apart, especially when there is a high degree of temporal variability in chlorophyll distribution (Hu et al. 2003).

Frontal Zones and Phytoplankton Ecology in the GOM

The concentration of phytoplankton biomass that occurs at some frontal zones influences the local ecology by increasing food availability for primary and secondary consumers such as zooplankton and fish (Holligan 1981; Lars et al. 1984; LeFevre 1986; Smith et al. 1986). Royer et al. (2004) compared satellite SST and plankton bloom data with airborne surveys of young tuna taken during summer in the Gulf of Lions (Mediterranean Sea) and found that in general the fish stayed close to transient fronts. Schick et al. (2004) compared aerial surveys of blue-fin tuna with SST in the Gulf of Maine and found that although patterns of tuna distribution were not entirely explained by frontal features, locations where bluefin tuna were seen where closer to fronts than locations where no tuna were seen. Loggerhead sea turtles (Polovina et al. 2000), Hawaiian swordfish (Seki et al. 2002), and sperm whales (Davis et al. 2002) have also been associated with oceanic fronts.

Identification of high productivity at frontal zones within the GOM would have a potentially significant impact on both commercial fishing and conservation efforts. Establishing a link between fronts and commercial would provide the fishing industry with a method for locating fishing areas. A link between fronts and protected marine species could target conservation efforts to specific areas. However, my study indicates that although some frontal zones can accumulate biomass, all fronts in the GOM (defined as areas of sharp changes in density) do not necessarily exhibit enhanced biomass. One problem could be the transitory nature of the fronts studied. According to Odum (1971), an edge effect or ecotone is created when separate ecosystems contact

each other. In an ecotone, the biological production is greater than within each individual ecosystem (Foerster 1996). Whether biomass at fronts is created by purely mechanical processes (convergence) or by physiological processes (increased growth rate), for a clear ecotone to be created, fronts would have to be persistent for a significant increase in phytoplankton to occur. Therefore, fronts would need to persist for several weeks for an increase in zooplankton and fish.

CONCLUSION

The main objective of the present research was to identify patterns in phytoplankton biomass and community structure at frontal zones within the northern Gulf of Mexico using chlorophyll *a* and carotenoid photopigment data derived from a combination of continuous fluorescence data and discrete HPLC data. Statistical results indicate that density fronts within the GOM do not exhibit the high phytoplankton biomass characteristic of fronts found in other areas. In addition, there were no significant differences in community structure across fronts.

The use of continuous fluorescence data to estimate chlorophyll *a* and algal group abundance assumes that the changes in the concentrations of these variables are linear. High and low concentrations in between discrete points can be averaged out. Using point-to-point linear regressions can decrease error associated with continuous chlorophyll calculations.

The formation of ecotones can be limited if fronts persist over short time scales. Short time scales can prevent the enhancement of biomass and the formation of distinct communities of phytoplankton by limiting the amount of phytoplankton accumulation, the mixing of phytoplankton communities with distinct structures, or by limiting aggregation resulting from increased growth rates.

The results of this study suggest that surface density fronts are not biologically important features in the GOM. Sharp gradients in light, salinity, and nutrients are not present in offshore surface waters of the GOM. Other factors, such as grazing and surface mixing could be more important in determining phytoplankton biomass at fronts.

LITERATURE CITED

Arrigo, KR, Robinson, DH, Worthen, DL, Dunbar, R B, DiTullio, GR, VanWoert, M, Lizoote, MP (1999) Phytoplankton community structure and the drawdown of nutrients and CO_2 in the Southern Ocean. Science 283(5400):365-367

Aubry, FB, Berton, A, Bastianini, M, Socal, G, Acri, F (2004) Phytoplankton succession in a coastal area of the NW Adriatic, over a 10-year sampling period (1990-1999). Continental Shelf Research 24: 97-115

Barlow, R. G., Mantoura, R. F. C, Cummings, D. G., Fileman, T. W. 1997. Pigment chemotaxonomic distributions of phytoplankton during summer in the western Mediterranean. Deep-Sea Research II 44(3-4): 833- 850.

Barnard, W.R., Froelich, P. N. 1981. Nutrient geochemistry of the Gulf of Mexico. NOAA/AOML Conference: Environmental Research Needs in the Gulf of Mexico, 30 September – 5 October 1979, Key Biscayne, FL. Miami, FL, p. 127.

Belabbassi, L. 2001. Importance of physical processes on near-surface nutrient distributions in summer in the northeastern Gulf of Mexico. Master's Thesis, Dept. of Oceanography, Texas A&M University, College Station, TX, 69 pp.

Biggs, D. C. 1992. Nutrients, plankton, and productivity in a warm-core ring in the western Gulf of Mexico. Journal of Geophysical Research 97: 2143-2154.

Biggs, D. C., Müller-Karger, F. E. 1994. Ship and satellite observations of chlorophyll stocks in interacting cyclone-anticyclone eddy pairs in the western Gulf of Mexico. Journal of Geophysical Research 99: 7371-7384.

Campbell, L., Nolla, H. A., Vaulot, D. 1994. The importance of *Prochlorococcus* to community structure in the central North Pacific Ocean. Limnology and Oceanography 39**:** 954-961.

Chen, X., Lohrenz, S. E., Wiesenburg, D. A. 2000. Distribution and controlling mechanisms of primary production on the Louisiana—Texas continental shelf. Journal of Marine Systems 25: 179-207.

Dagg, M. J. 1995. Copepod grazing and the fate of phytoplankton in the northern Gulf of Mexico. Continental Shelf Research 15: 1303-1317.

Dagg, M. J., Breed, G. A. 2003. Biological effects of Mississippi River nitrogen on the northern Gulf of Mexico – a review and synthesis. Journal of Marine Systems 43: 133-152.

Dahl, K., Repeta, D., Goericke, R. 2003. Reconstructing the phytoplankton community structure of the Cariaco Basin during the Younger Dryas cold event using chlorine steryl esters. Geophysical Research Abstracts 5(01174).

Davis, R. W., Ortega-Ortiz, J. G., Ribic, C. A., Evans, W. E., Biggs, D. C., Ressler, P. H., Cady, R. B., Leben, R. R., Mullin, K. D., Wursig, B. 2002. Cetacean habitat in the northern oceanic Gulf of Mexico. Deep-Sea Research 49: 121-142.

DiTullio, G. R., Geesey, M. E., Jones, D. R., Daly, K. L., Campbell, L., Smith, W. O. 2003. Phytoplankton assemblage structure and primary productivity along 170°W in the South Pacific Ocean. Marine Ecology Progress Series 255: 55-80.

Dortch, Q., Rabalais, N. N., Turner, R. E., Rowe, G. T. 1994. Respiration rates and hypoxia on the Louisiana Shelf. Estuaries 17(4): 862-872.

Ducobu, H., Huisman, J., Jonker, R. R., Mur, L. R. 1998. Competition between a prochlorophyte and a cyanobacterium under various phosphorus regimes: comparison with the Droop model. Journal of Phycology 34(3): 467-476.

Dustan, P., Pinckney, J. L. 1989. Tidally induced estuarine phytoplankton patchiness. Limnology and Oceanography 34(2): 410-419.

Ehlers, K. M., Samuel, A. D. T, Berg, H. C., Montgomery, R. 1996. Do cyanobacteria swim using traveling surface waves? Proceedings of the National Academy of Sciences of the United States of America 93(16): 8340-8343.

Eppley, R. W. 1972. Temperature and phytoplankton growth in the sea. Fishery Bulletin 70(4): 1063-1085.

Eppley, R. W., Thomas, W. H. 1969. Comparison of half-saturation constants for growth and nitrate uptake of marine phytoplankton. Journal of Phycology 5(4): 375.

Etnoyer, P., Canny, D., Mate, B., Morgan, L. 2004. Persistent pelagic habits in the Baja California to Bering Sea (B2B) ecoregion. Oceanography 17(1): 90-101.

Fahnenstiel, G. L., McCormick, M. J., Lang, G. A., Redalje, D. G., Lohrenz, S. E., Markowitz, M., Wagoner, B., Carrick, H. J. 1995. Taxon-specific growth and loss rates for dominant phytoplankton populations from the northern Gulf of Mexico. Marine Ecology Progress Series 117: 229-239.

Falkowski, P. G., LaRoche, J. 1991. Acclimation to spectral irradiance in algae. Journal of Phycology 27:8-14.

Falkowski, P. G., Ziemann, D., Kolber, Z., Bienfang, P. K. 1991. Role of eddy pumping in enhancing primary production in the ocean. Nature 352(4): 55-88.

Falkowski, P. G., Raven, J. A. 1997. Aquatic Photosynthesis. Blackwell Science. Malden, Massachusetts, 375 pp.

Fiala, M., Delille, B., Dubreuil, C., Kopczyńska, E., Leblanc, K., Morvan, J., Quéguiner, B., Blain, S., Cailliau, C., Conan, P., Corvaisier, R., Denis, M., Frankignoulle, M., Oriol, L., Roy, S. 2003. Mesoscale surface distribution of biogeochemical characteristics in the Crozet Basin frontal zones (South Indian Ocean). Marine Ecology Progress Series 249: 1-14.

Flint, M. V., Sukhanova, I. N. 2002. The influence of the coastal fronts around the Pribilof Islands (Bering Sea) on the distribution and dynamics of phytoplankton. Marine Biology 42(Suppl. 1): S63-S78.

Foerster, J. W. 1996. The edge effect in the northeast North Pacific Ocean. Ciencias Marinas 22(2): 175-190.

Franks, P. J. S. 1992a. Phytoplankton blooms at fronts: patterns, scales, and physical forcing mechanisms. Reviews in Aquatic Sciences 6(2): 121-137.

Franks, P. J. S. 1992b. Sink or swim: accumulation of biomass at fronts. Marine Ecology Progress Series 82:1-12.

Franks, P. J. S. 2001. Phytoplankton blooms in a fluctuating environment: the roles of plankton response time scales and grazing. Journal of Plankton Research 23(12): 1433-1441.

Gibb, S. W., Cummings, D. G., Irigoien, X., Barlow, R. G., Fauzi, R., Mantoura, C. 2001. Phytoplankton pigment chemotaxonomy of the northeastern Atlantic. Deep-Sea Research 48: 795-823.

Gilbes, F., Tomas, C., Walsh, J. J., Müller-Karger, F. E. 1996. An episodic chlorophyll plume on the West Florida Shelf. Continental Shelf Research 16(9): 1201-1224.

Goericke, R. 2002. Top-down control of phytoplankton biomass and community structure in the monsoonal Arabian Sea. Limnology and Oceanography 47(5): 1307-1323.

Goericke, R., Montoya, J. P. 1998. Estmating the contribution of microalgal taxa to chlorophyll a in the field—variations of pigments rations under nutrient- and light-limited growth. Marine Ecology Progress Series 169: 97-112.

Gonzalez-Rodas, G. E. 1999. Physical forcing of the primary productivity in the northwestern Gulf of Mexico, Ph.D. dissertation, Dept. of Oceanography, Texas A&M University, College Station, TX, 142 pp.

Gulf of Mexico Region AVHRR Images (n.d.). Retrieved June 2004 from http://fermj.jhuapl.edu/avhrr/gm/index.html

Guillard, R. R., Kilham, P., Jackson, T. A. 1973. Kinetics of silicon-limited growth in the marine diatom *Thalassiosira pseudonana* Hasle and heimdal *Cyclotella nana* Hustedt. Journal of Phycology 9(3): 233-237.

Hallegraeff, G. M. 1981. Seasonal study of phytoplankton pigments and species at a coastal station off Sydney: importance of diatoms and nanoplankton. Marine Biology 61: 107-118.

Hardin, G. 1960. The competitive exclusion principle. Science 131: 1292-1297.

Ho, C. L., Barrett, B. B. 1977. Distribution of nutrients in Louisiana's coastal waters influenced by the Mississippi River. Estuarine Coastal Marine Science 5: 173-195.

Holligan, P. M. 1981. Biological implications of fronts on the northwest European continental shelf. Phil. Trans. R. Soc. Lond. *A*. 302: 547-562.

Hu, C., Muller-Karger, F. E., Biggs, D. C., Carder, K. L., Nababan, B., Nadeau, D., Vanderbloemen, J. 2003. Comparison of ship and satellite bio-optical measurements on the continental margin of the NE Gulf of Mexico. International Journal of Remote Sensing 24(13): 2597-2612.

Jeffrey, S. W., Mantoura, R. F. C., Wright, W. (Eds). 1997. Phytoplankton pigments in oceanography. Guidelines to Modern Methods. UNESCO, Paris.

Jeong, H. J., Yoo, Y. D., Kim, S. T., Kang, N. S. 2004. Feeding by the heterotrophic dinoflagellate *Protoperidinium bipes* on the diatom *Skeletonema costatum*. Aquatic Microbial Ecology 36(2): 171-179.

Jochens, A. E., DiMarco, S. F., Nowlin, W. D., Reid, R. O., Kennicutt, M. C. 2002. Northeastern Gulf of Mexico Chemical Oceanography and Hydrography Study. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA., OCS Study MMS 2002-055. 586 pp.

Jones, B. H., Halpern, D. 1981. Biological and physical aspects of a coastal upwelling event observed during March-April 1974 off northwest Africa. *Deep-Sea Research* 28A: 71-81.

Kana, T. M., Gilbert, P. M., Goericke, R., Welschmeyer, N. A. 1988. Zeaxanthin and β-carotene in *Synechococcus* WH 7803. Limnology and Oceanography 33: 1623-1627.

Kang, S. H., Fryxell, G. A. 1991. Most abundant diatoms species in water column assemblages from five Leg 119 drill sites in Prydz Bay, Antarctica: distribtutional patterns. In: Larson, B. (ed) Proc Ocean Drilling Program, Scientific Results. Texas A&M University Press College Station, TX, p. 645-666.

Kirk, J. T. O. 1994. The photosynthetic apparatus of aquatic plants. In: Light & Photosynthesis in Aquatic Ecosystems. Cambridge University Press, Cambridge. p. 217-251.

Knauss, J. A. 1996. A stratified ocean. In: Introduction to Physical Oceanography. Prentice-Hall, Upper Saddle River, New Jersey. p. 24-38.

Kopczyńska, E. E., Fiala, M., 2003. Surface phytoplankton composition and carbon biomass distribution in the Crozet Basin during austral summer of 1999: variability across frontal zones. Polar Biology 27: 17-28.

Kostianoy, A. G., Ginzburg, A. I, Frankignoulle, M., Delille, B. 2004. Fronts in the Southern Indian Ocean as inferred from satellite sea surface temperature data. Journal of Marine Systems 45(1-2): 55-73.

Lambert, C.D., Bianchi, T.S, Santschi, P.H. 1999. Cross-shelf changes in phytoplankton community composition in the Gulf of Mexico (Texas shelf/slope): the use of plant pigments as biomarkers. Continental Shelf Research 19: 1-21.

Laubscher, R. K., Perissinotto, R., McQuiad, C. D. 1993. Phytoplankton production and biomass at frontal zones in the Atlantic sector of the Southern-Ocean. Polar Biology 7: 471-481.

Laurs, M. L. P., Fieldler, Montgomery, D. R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Research 31: 1085-1099.

LeFevre, J. 1986. Aspects of the biology of frontal zones. Advances in Marine Biology 23: 163-299.

Letelier, R.M., Bidigare, R. R., Hebel, D. V., Ondrusek, M., Winn, C. D., Karl, D. M. 1993. Temporal variability of phytoplankton community structure based on pigment analysis. Limnology and Oceanography 38(7): 1420-1437.

Levins, R. 1979. Coexistence in variable environments. The American Naturalist 95: 137-145.

Litchman, E. 2000. Growth rates of phytoplankton under fluctuating light. Freshwater Biology 44: 223-235.

Lohrenz, S. E., Carroll, C. L., Weidemann, A. D., Tuel, M. 2003. Variations in phytoplankton pigments, size structure and community composition related to wind forcing and water mass properties on the North Carolina inner shelf. Continental Shelf Research 23: 1447-1464.

Lutjeharms, J. R. E., Valentine, H. R. 1984. Southern Ocean thermal fronts south of Africa. Deep-Sea Research 31(12): 1461-1475.

Lutjeharms, J. R. E, Foldvik, A. 1986. The thermal structure of the upper ocean layers between Africa and Antarctica during the period December 1978 to March 1979. South African Journal of Antarctic Research 16(1): 13-20

MacIntyre, H. I., Kana, T. M., Anning, T., and Geider, R. J. 2002. Photoacclimation of photosynthesis irradiance response curves and photosynthetic pigments in microalgae and cyanobacteria. Journal of Phycology 38: 17-38.

Mackey, M. D., Mackey, D. J., Higgins, H. W., Wright, S. W. 1996. CHEMTAX – a program for estimating class abundances from chemical markers: application to HPLC measurements of phytoplankton. Marine Ecology Progress Series 144: 265-283.

Mackey D. J., Higgins, H. W., Mackey, M. D., Holdsworth, D. 1998. Algal class abundances in the western equatorial Pacific: Estimation from HPLC measurement of chloroplast pigments using CHEMTAX. Deep-Sea Research Part I 45(9): 1441-1468.

Malakoff, D. 2004. New tools reveal treasures at ocean hot spots. Science 304: 1104-1105.

Margalef, R. 1978. Diversity. In: Sournia, A. (ed) Phytoplankton Manual. United Nations Educational, Scientific and Cultural Organization, Paris, pp. 251-260.

McGillicuddy, D. J., Signell, R. P., Stock, C. A., Keafer, B. A., Keller, M. D., Hetland, R. D., Anderson, D. M. 2003. A mechanism for offshore initiation of harmful algal blooms in the coastal Gulf of Maine. Journal of Plankton Research 25(9): 1131-1138.

Millie, D. F., Paerl, H. W., Hurley, J. P. 1993. Microalgal pigment assessments using high-performance liquid chromatography: a synopsis of organismal and ecological applications. Canadian Journal of Fisheries and Aquatic Sciences 50: 2513-2527.

Mitchell, G. B., Brody, E., Holm-Hansen, O., McClain, C. R., Bishop, J. 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean. Limnology and Oceanography 36: 1662-1677.

Muller-Karger, F. E., Walsh, J. J., Evens, R. H., Meyers, M. B. 1991. On the seasonal phytoplankton concentration and sea surface temperature cycles of the Gulf of Mexico as determined by satellites. Journal of Geophysical Research 97(C7): 12,645-12,665.

Narayanan, C., Garvine, R. W. 2002. Large scale buoyancy driven circulation on the continental shelf. Dynamics of Atmospheres and Oceans 36: 125-152.

Nowlin, W. D., Jochens, A. E., Reid, R. O., DiMarco, S. F. 1998. Physical Texas-Louisiana Shelf Circulation and Transport Processes Study: Synthesis Report. Volume 1: Technical Report. U.S. Dept. of the Interior, New Orleans, p. 17-82.

Odum, E. P. 1971. Fundamentals of Ecology. Saunders, Philadelphia.

Olson, D. B., Backus, R. H. 1985. The concentration of organisms at fronts: a cold-water fish and a warm-core Gulf Stream ring. Journal of Marine Research 43: 113-137.

Olson, R. J., Chisholm, S. W., Zettler, E. R., Altabet, M. A., Dusenberry, J. A. 1990. Spatial and temporal distributions of prochlorophyte picoplankton in the North Atlantic Ocean. Deep-Sea Research 37: 1033-1051.

Örnólfsdóttir, E. B., Lumsden, S. E., Pinckney, J. L. 2004a. Phytoplankton community growth-rate response to nutrient pulses in a shallow turbid estuary, Galveston Bay, Texas. Journal of Plankton Research 26(3): 325-339.

Örnólfsdóttir, E. B., Lumsden, S. E., Pinckney, J. L. 2004b. Nutrient pulsing as a regulator of phytoplankton abundance and community composition in Galveston Bay, Texas. Journal of Experimental Marine Biology and Ecology In Press.

Osmond, C. B. 1994. Photoinhibition of Photosynthesis. N. R. Baker, J. R. Bowyer (eds.). BIOS Scientific, Oxford, UK , pp. 1-24.

Parsons, T. R., Maita, Y., Lalli, C. M. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford, UK., 173 pp.

Pinckney, J., Dustan, P. 1990. Ebb-tidal fronts in Charleston Harbor, South Carolina: physical and biological characteristics. Estuaries 13(1): 1-7.

Pinckney, J. L., Millie, D. F., Howe, K. E., Paerl, H. W., Hurley, J. P. 1996. Flow scintillation counting of ^{14}C-labeled microalgal photosynthetic pigments. Journal of Plankton Research 18:1867-1880.

Pinckney, J. L., Paerl, H. W., Harrington, M. B., Howe, K. E. 1998. Annual cycles of phytoplankton community-structure and bloom dynamics in the Neuse River Estuary, North Carolina. Marine Biology 131: 371-381.

Pingree, R., Pugh, P., Holligan, P. M., Forster, G. 1975. Summer phytoplankton blooms and red tides in the approaches to the English Channels. Nature 258: 672-677.

Polovina, J. J., Howell, E., Kobayashi, D. R., Seki, M. P. 2000. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography 49: 469-483.

Qian, Y., Jochens, A.E., Kennicutt II, M.C, Biggs, D.C. 2003. Spatial and temporal variability of phytoplankton biomass and community structure over the continental margin of the northeast Gulf of Mexico based on pigment analysis. Continental Shelf Research 23, 1-17.

Rabalais, N. N., Turner, Justić, R. E. T. D., Dortch, Q., Wiseman, W. J., Gupta, B. K. S. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19(2B): 386-407.

Rabalais, N. N., Turner, R. E., Wiseman, W. J. 2002. Gulf of Mexico hypoxia, aka "the dead zone". Annual Review of Ecology and Systematics 33: 235-263.

Royer, F., Fromentin, J. M. Gaspar, P. 2004. Association between bluefin tuna schools and oceanic features in the western Mediterranean. Marine Ecology-Progress Series 269: 249-263.

Sahl, L. E., Merrell, W. J., Biggs, D. C. 1993. The influence of advection on the spatial variability of nutrient concentrations on the Texas-Louisiana continental shelf. Continental Shelf Research 13(2/3): 233-251.

Schick, R.S., Goldstein, J., Lutcavage, M. E. 2004. Bluefin tuna (*Thunnus thynnus*) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994-96). Fisheries Oceanography 13(4): 225-238.

Schluessel, P., Emmery, W. J., Grassl, H., Mammen, T. 1990. On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperature. Journal of Geophysical Research 95(C8): 13,341-13,356.

Schluter, L., Møhlenberg, F., Havskum, H., Larsen, S. 2000. The use of phytoplankton pigments for identifying and quantifying phytoplankton groups in coastal areas: testing the influence of light and nutrients on pigment/chlorophyll *a* ratios. Marine Ecology Progress Series 192: 49-63.

Seki, M. P., Polovina, J. L., Kobayashi, D. R., Bidigare, R. R., Mitchum, G. T. 2002. An oceanographic characterization of swordfish (*Xiphias gladius*) longline fishing grounds in the springtime subtropical North Pacific. Fisheries Oceanography 11(5): 251-266.

Serodio, J. 2003. A chlorophyll fluorescence index to estimate short-term rates of photosynthesis by intertidal microphytobenthos. Journal of Phycology 39(1): 33-46.

Simpson, J. H., Tett, P. B., Argotte-Espinoza, M. L., Edwards, A., Jones, K. J., Savidge, G. 1982. Mixing and phytoplankton growth around an island in a stratified sea. Continental Shelf Research 1(1):15-31.

Smith, R., Dustan, P., Au, D., Baker, K. S., Dunlap, E. A. 1986. Distribution of cetaceans and sea surface chlorophyll concentrations in the California current. Marine Biology 91: 385-402.

Sommer, U. 1989. The role of competition for resources in phytoplankton succession. In: Sommer, U. (ed), Plankton Ecology: Succession in Plankton Communities. Springer-Verlag, Berlin, pp. 57-106.

Sommer, U. 1995. An experimental test of the intermediate disturbance hypothesis using cultures of marine phytoplankton. Limnology and Oceanography 40(7): 1271-1277.

Sommer, U. 1999. Competition and coexistence. Nature 402: 366-367.

Stegmann, P. M., Ullman, D. S. 2004. Variability in chlorophyll and sea surface temperature fronts in the Long Island Sound outflow region from satellite observations. Journal of Geophysical Research–Oceans 109(C7).

Steidinger, K. A., Vargo, G. A., Tester, P. A., Tomas, C. R. 1998. Bloom dynamics and physiology of *Gymnodinium breve* with emphasis on the Gulf of Mexico. In: Anderson, D. M., Cembella, A. D., Hallegraeff, G. M. (eds), The Physiological Ecology of Harmful Algal Blooms, NATO ASI Series, Series G, Vol. 41. Springer, New York, pp. 133-145.

Strickland, J. D. H., Parsons, T. R. 1972. A Practical Handbook of Seawater Analysis. Fisheries Research Board of Canada, Ottawa, p. 203.

Thomas, A. C., Townsend, D. W., Weatherbee, R. 2003. Satellite-measured phytoplankton variability in the Gulf of Maine. Continental Shelf Research 23: 971-989.

Tilman, D. 1977. Resource competition between planktonic algae: an experimental and theoretical approach. Ecology 58: 338-348.

Tilman, D. 1982. Phytoplankton community ecology: the role of limiting nutrients. Annual Review of Ecology and Systematics 13: 349-372.

Tilman, D., Kiesling, R., Sterner, R., Kilham, S. S., Johnson, F. A. 1986. Green, bluegreen, and diatom algae: taxonomic differences in competitive ability for phosphorus, silicon and nitrogen. Archiv für Hydrobiologie 106: 473-485.

Titman, D. 1976. Ecological competition between algae: experimental confirmation of resource-based competition theory. Science 192: 463-464.

Vaillancourt, R. D., Sambrotto, R. N., Green, S., Matsuda, A. 2003. Phytoplankton biomass and photosynthetic competency in the summertime Mertz Glacier Region of East Antarctica. Deep-Sea Research Part II 50(8-9): 1415-1440.

Van Heukelem, L., Lewitus, A. J., Kana, T. M. 1992. High-performance liquid chromatography of phytoplankton pigments using a polymeric reversed-phase C_{18} column. Journal of Phycology 28:867-872.

Van Heukelem, L., Lewitus, A.J., Kana, T. M., Craft, N. E. 1994. Improved separations of phytoplankton pigments using temperature-controlled high performance liquid chromatography. Marine Ecology Progress Series 114:303-313.

Vargo, G. A., Howard-Shamblott, D. 1990. Phosphorus dynamics in *Ptychodiscus brevis*: cell phosphorus, uptake and growth requirements. In: Graneli, E. (ed) Toxic Marine Phytoplankton. Elsevier, New York, pp. 324-329.

Walker, N. D., Fargion, G. S., Rouse, L. J., Biggs, D. C. 1994. The great flood of summer 1993: Mississippi River discharge studied. EOS, Transactions, American Geophysical Union 75(36): 409, 414-415.

Wawrik, B., Paul, J.H., Campbell, L., Griffin, D., Houchin, L., Fuentes-Ortega, A., Muller-Karger, F. 2003. Vertical structure of the phytoplankton community associated with a coastal plume in the Gulf of Mexico. Marine Ecology Progress Series 251, 87-101.

Wright, S. W., Jeffrey, S. W., Mantoura, R. F. C., Llewellyn, C. A., Bjornland, T., Repeta, D., Welschmeyer N. A. 1991. Improved HPLC method for the analysis of chlorophylls and carotenoids from marine phytoplankton. Marine Ecology Progress Series 77: 183-196.

Wright, S.W., Thomas, D. P., Marchant, H. J., Higgins, H. W., Mackey, M. D., Mackey, D. J. 1996. Analysis of phytoplankton of the Australian sector of the Southern Ocean: comparisons of microscopy and size frequency data with interpretations of pigment HPLC data using the "CHEMTAX' matrix factorization program. Marine Ecology Progress Series 144, 285-298.

Wright, S. W., van den Enden, R. L. 2000. Phytoplankton community structure and stocks in the East Antarctic marginal ice zone (BROKE survey, January-March 1996) determined by CHEMTAX analysis of HPLC pigment signatures. Deep-Sea Research II 47: 2363-2400.

APPENDIX A

Tables showing mean, median, and range of chl *a* and algal group concentrations for each cruise; mean concentration of chl *a* and algal groups across each front; and results of non-parametric Kruskal-Wallis and Dunnett T3 statistical tests comparing algal group abundance (μg/L) and diversity (Shannon-Weaver Index) both between locations within fronts (before front, front, and after front) and between the fronts themselves for each of the four cruises studies.

Table A.1. Algal group concentration (mean, median, and range) in µg/L for summer 2002, summer 2003, fall 2003, and spring 2004 cruises.

Cruise	Algal Group	Mean Concentration (µg/L)	Median Concentration (µg/L)	Concentration Range
Summer 2002	Total chl *a*	1.17×10^{-1}	1.02×10^{-1}	$6.80 \times 10^{-3} – 1.33$
	Prasinophytes	2.67×10^{-4}	2.69×10^{18}	0 – 0.06
	Dinoflagellates	1.95×10^{-3}	2.35×10^{-4}	$0 – 3.37 \times 10^{12}$
	Cryptophytes	7.58×10^{-4}	4.96×10^{-4}	0 – 0.02
	Haptophytes	7.46×10^{-3}	5.54×10^{-3}	0 – 0.08
	Chrysophytes	2.50×10^{-2}	1.48×10^{-2}	0 – 0.23
	Chlorophytes	3.11×10^{-4}	2.64×10^{-4}	0 – 0.00
	Cyanobacteria	8.16×10^{-2}	7.89×10^{-2}	0 – 0.91
	Diatoms	6.72×10^{-5}	8.78×10^{-7}	0 – 0.23
Summer 2003	Total chl *a*	1.06	0.29	0 – 11.7
	Prasinophytes	0	0	$0 – 2.66 \times 10^{16}$
	Dinoflagellates	0.01	0	0 – 0.45
	Cryptophytes	0.03	0	0 – 1.47
	Haptophytes	0.04	0.01	0 – 0.52
	Chrysophytes	0	0	0 – 0.11
	Chlorophytes	0.8	0	0 – 3.64
	Cyanobacteria	0.74	0.24	0 – 11.70
	Diatoms	0.15	0.03	0 – 2.45
Fall 2003	Total chl *a*	0.12	0.11	0 – 0.40
	Dinoflagellates	0.00	0.00	0 – 0.03
	Chrysophytes	0.01	0.00	0 – 0.01
	Chlorophytes	0.09	0.09	0 – 0.32
	Cyanobacteria	0.02	0.02	0 – 0.10
	Diatoms	0.00	0.00	0 – 0.04
Spring 2003	Total chl *a*	0.82	0.77	0 – 4.16
	Prasinophytes	0.04	0.03	0 – 0.20
	Dinoflagellates	0.06	0.02	0 – 0.64
	Cryptophytes	0.05	0.05	0 – 0.28
	Haptophytes	0.02	0.01	0 – 0.09
	Chrysophytes	0.06	0.05	0 – 0.40
	Chlorophytes	0.13	0.10	0 – 0.59
	Cyanobacteria	0.09	0.05	0 – 0.41
	Diatoms	0.36	0.25	0 – 2.04

Table A.2. Mean chl *a* and algal group concentrations (µg/L) for each front location.

Cruise	Front	Algal Group	Mean Conc. Before Front (µg/L)	Mean Conc. Front (µg/L)	Mean Conc. After Front (µg/L)
Summer 2002	Front 1	Total Chl *a*	1.9×10^{-1}	1.9×10^{-1}	1.9×10^{-1}
		Prasinophytes	4.79×10^{-3}	4.77×10^{-3}	4.72×10^{-3}
		Dinoflagellates	2.37×10^{-5}	2.36×10^{-5}	2.34×10^{-5}
		Cryptophytes	7.34×10^{-4}	7.30×10^{-4}	7.24×10^{-4}
		Haptophytes	6.81×10^{-3}	6.78×10^{-3}	6.72×10^{-3}
		Chrysophytes	2.52×10^{-2}	2.50×10^{-2}	2.48×10^{-2}
		Chlorophytes	3.58×10^{-4}	3.56×10^{-4}	3.53×10^{-4}
		Cyanobacteria	1.5×10^{-1}	1.5×10^{-1}	1.5×10^{-1}
		Diatoms	2.34×10^{-7}	2.33×10^{-7}	2.32×10^{-7}
	Front 2	Total Chl *a*	3.90×10^{-1}	4.80×10^{-1}	4.60×10^{-1}
		Prasinophytes	1.19×10^{-18}	1.45×10^{-18}	1.38×10^{-18}
		Dinoflagellates	1.60×10^{-2}	1.94×10^{-2}	1.85×10^{-2}
		Cryptophytes	2.71×10^{-3}	3.29×10^{-3}	3.13×10^{-3}
		Haptophytes	1.81×10^{-2}	2.20×10^{-2}	2.10×10^{-2}
		Chrysophytes	1.60×10^{-1}	1.90×10^{-1}	1.80×10^{-1}
		Chlorophytes	1.40×10^{-3}	1.70×10^{-3}	1.62×10^{-3}
		Cyanobacteria	1.60×10^{-1}	1.90×10^{-1}	1.80×10^{-1}
		Diatoms	3.73×10^{-4}	4.53×10^{-4}	4.32×10^{-4}
	Front 3	Total Chl *a*	8.69×10^{-2}	9.05×10^{-2}	9.17×10^{-2}
		Prasinophytes	1.04×10^{-18}	1.09×10^{-18}	1.10×10^{-18}
		Dinoflagellates	1.51×10^{-3}	1.57×10^{-3}	1.59×10^{-3}
		Cryptophytes	4.39×10^{-4}	4.56×10^{-4}	4.63×10^{-4}
		Haptophytes	4.57×10^{-3}	4.75×10^{-3}	4.82×10^{-3}
		Chrysophytes	2.27×10^{-2}	2.36×10^{-2}	2.39×10^{-2}
		Chlorophytes	2.25×10^{-4}	2.34×10^{-4}	2.38×10^{-4}
		Cyanobacteria	5.59×10^{-2}	5.82×10^{-2}	5.90×10^{-2}
		Diatoms	9.08×10^{-7}	9.44×10^{-7}	9.58×10^{-7}
Summer 2003	Front 1	Total Chl *a*	1.69×10^{-1}	1.73×10^{-1}	1.71×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	8.23×10^{-5}	8.43×10^{-5}	8.33×10^{-5}
		Cryptophytes	1.41×10^{-3}	1.44×10^{-3}	1.42×10^{-3}
		Haptophytes	7.97×10^{-5}	8.17×10^{-5}	8.07×10^{-5}
		Chrysophytes	5.43×10^{-5}	5.57×10^{-5}	5.50×10^{-5}
		Chlorophytes	1.02×10^{-3}	1.05×10^{-3}	1.03×10^{-3}
		Cyanobacteria	1.64×10^{-1}	1.68×10^{-1}	1.66×10^{-1}
		Diatoms	2.32×10^{-3}	2.38×10^{-3}	2.35×10^{-3}
	Front 2	Total Chl *a*	1.36×10^{-1}	1.47×10^{-1}	1.51×10^{-1}
		Prasinophytes	3.51×10^{-19}	0.00	0.00
		Dinoflagellates	6.74×10^{-5}	6.91×10^{-5}	7.09×10^{-5}
		Cryptophytes	1.15×10^{-3}	1.18×10^{-3}	1.21×10^{-3}
		Haptophytes	6.53×10^{-5}	6.70×10^{-5}	6.86×10^{-5}
		Chrysophytes	4.45×10^{-5}	4.56×10^{-5}	4.68×10^{-5}
		Chlorophytes	8.36×10^{-4}	8.58×10^{-4}	8.80×10^{-4}
		Cyanobacteria	1.26×10^{-1}	1.37×10^{-1}	1.40×10^{-1}
		Diatoms	7.52×10^{-3}	8.41×10^{-3}	8.62×10^{-3}

Table A.2. (cont'd).

Cruise	Front	Algal Group	Mean Conc. Before Front (µg/L)	Mean Conc. Front (µg/L)	Mean Conc. After Front (µg/L)
Summer 2003	Front 3	Total Chl *a*	1.53×10^{-1}	1.53×10^{-1}	1.53×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	1.18×10^{-18}	1.19×10^{-18}	1.19×10^{-18}
		Cryptophytes	2.22×10^{-3}	2.22×10^{-3}	2.22×10^{-3}
		Haptophytes	4.75×10^{-5}	4.76×10^{-5}	4.75×10^{-5}
		Chrysophytes	3.64×10^{-5}	3.65×10^{-5}	3.65×10^{-5}
		Chlorophytes	1.61×10^{-3}	1.62×10^{-3}	1.61×10^{-3}
		Cyanobacteria	1.31×10^{-1}	1.32×10^{-1}	1.31×10^{-1}
		Diatoms	1.76×10^{-2}	1.76×10^{-2}	1.76×10^{-2}
	Front 4	Total Chl *a*	1.52×10^{-1}	1.52×10^{-1}	1.51×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	1.54×10^{-4}	1.53×10^{-4}	1.53×10^{-4}
		Cryptophytes	2.63×10^{-3}	2.62×10^{-3}	2.61×10^{-3}
		Haptophytes	1.49×10^{-4}	1.49×10^{-4}	1.48×10^{-4}
		Chrysophytes	1.01×10^{-4}	1.01×10^{-4}	1.01×10^{-4}
		Chlorophytes	1.91×10^{-3}	1.91×10^{-3}	1.89×10^{-3}
		Cyanobacteria	1.43×10^{-1}	1.43×10^{-1}	1.42×10^{-1}
		Diatoms	4.33×10^{-3}	4.33×10^{-3}	4.30×10^{-3}
	Front 5	Total Chl *a*	7.35×10^{-1}	6.35×10^{-1}	5.95×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	3.92×10^{-4}	3.39×10^{-4}	3.18×10^{-4}
		Cryptophytes	9.79×10^{-3}	8.47×10^{-3}	7.94×10^{-3}
		Haptophytes	3.97×10^{-4}	3.44×10^{-4}	3.22×10^{-4}
		Chrysophytes	2.79×10^{-4}	2.41×10^{-4}	2.26×10^{-4}
		Chlorophytes	7.12×10^{-3}	6.15×10^{-3}	5.77×10^{-3}
		Cyanobacteria	6.73×10^{-1}	5.82×10^{-1}	5.45×10^{-1}
		Diatoms	4.40×10^{-2}	3.81×10^{-2}	3.57×10^{-2}
	Front 6	Total Chl *a*	4.16×10^{-1}	2.84×10^{-1}	3.29×10^{-1}
		Prasinophytes	0.00	9.52×10^{-18}	0.00
		Dinoflagellates	2.22×10^{-4}	1.67×10^{-4}	3.32×10^{-4}
		Cryptophytes	5.54×10^{-3}	3.48×10^{-3}	5.68×10^{-3}
		Haptophytes	2.25×10^{-4}	1.65×10^{-4}	3.22×10^{-4}
		Chrysophytes	1.58×10^{-4}	1.14×10^{-4}	2.19×10^{-4}
		Chlorophytes	4.03×10^{-3}	2.53×10^{-3}	4.12×10^{-3}
		Cyanobacteria	3.81×10^{-1}	2.13×10^{-1}	3.09×10^{-1}
		Diatoms	2.49×10^{-2}	1.14×10^{-2}	9.35×10^{-3}
	Front 7	Total Chl *a*	2.15×10^{-1}	2.14×10^{-1}	2.18×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	1.37×10^{-6}	1.37×10^{-6}	1.39×10^{-6}
		Cryptophytes	2.76×10^{-3}	2.76×10^{-3}	2.80×10^{-3}
		Haptophytes	1.32×10^{-4}	1.31×10^{-4}	1.33×10^{-4}
		Chrysophytes	9.11×10^{-5}	9.09×10^{-5}	9.23×10^{-5}
		Chlorophytes	2.01×10^{-3}	2.00×10^{-3}	2.03×10^{-3}
		Cyanobacteria	2.01×10^{-1}	2.00×10^{-1}	2.03×10^{-1}
		Diatoms	9.16×10^{-3}	9.14×10^{-3}	9.28×10^{-3}

Table A.2. (cont'd).

Cruise	Front	Algal Group	Mean Conc. Before Front (µg/L)	Mean Conc. Front (µg/L)	Mean Conc. After Front (µg/L)
Summer 2003	Front 8	Total Chl *a*	3.14×10^{-1}	2.18×10^{-1}	1.35×10^{-1}
		Prasinophytes	0.00	0.00	0.00
		Dinoflagellates	7.07×10^{-5}	4.90×10^{-5}	3.03×10^{-5}
		Cryptophytes	1.21×10^{-3}	8.38×10^{-4}	5.18×10^{-4}
		Haptophytes	6.85×10^{-5}	4.75×10^{-5}	2.93×10^{-5}
		Chrysophytes	4.67×10^{-5}	3.23×10^{-5}	2.00×10^{-5}
		Chlorophytes	8.78×10^{-4}	6.08×10^{-4}	3.76×10^{-4}
		Cyanobacteria	3.10×10^{-1}	2.15×10^{-1}	1.33×10^{-1}
		Diatoms	1.99×10^{-3}	1.38×10^{-3}	8.54×10^{-4}
	Front 9	Total Chl *a*	2.78×10^{-1}	2.76×10^{-1}	2.74×10^{-1}
		Prasinophytes	2.12×10^{-18}	0.00	0.00
		Dinoflagellates	2.34×10^{-4}	8.09×10^{-19}	8.05×10^{-19}
		Cryptophytes	2.34×10^{-3}	2.88×10^{-3}	2.87×10^{-3}
		Haptophytes	2.94×10^{-2}	3.10×10^{-2}	3.09×10^{-2}
		Chrysophytes	6.57×10^{-19}	6.19×10^{-19}	6.16×10^{-19}
		Chlorophytes	1.70×10^{-3}	2.10×10^{-3}	2.09×10^{-3}
		Cyanobacteria	1.85×10^{-1}	2.15×10^{-1}	2.14×10^{-1}
		Diatoms	5.42×10^{-2}	2.49×10^{-2}	2.48×10^{-2}
Fall 2003	Front 1	Total Chl *a*	1.10×10^{-1}	1.11×10^{-1}	1.08×10^{-1}
		Dinoflagellates	0.00	0.00	0.00
		Chrysophytes	1.84×10^{-18}	1.85×10^{-18}	1.81×10^{-18}
		Chlorophytes	9.36×10^{-2}	9.44×10^{-2}	9.22×10^{-2}
		Cyanobacteria	1.34×10^{-2}	1.36×10^{-2}	1.32×10^{-2}
		Diatoms	2.95×10^{-3}	2.97×10^{-3}	2.90×10^{-3}
	Front 2	Total Chl *a*	2.05×10^{-1}	1.88×10^{-1}	2.06×10^{-1}
		Dinoflagellates	0.00	0.00	0.00
		Chrysophytes	6.39×10^{-3}	5.86×10^{-3}	6.42×10^{-3}
		Chlorophytes	1.71×10^{-1}	1.52×10^{-1}	1.67×10^{-1}
		Cyanobacteria	2.05×10^{-2}	2.39×10^{-2}	2.62×10^{-2}
		Diatoms	6.74×10^{-3}	5.59×10^{-3}	6.12×10^{-3}
	Front 3	Total Chl *a*	1.12×10^{-1}	1.14×10^{-1}	1.10×10^{-1}
		Dinoflagellates	1.32×10^{-6}	4.33×10^{-6}	4.18×10^{-6}
		Chrysophytes	6.34×10^{-3}	8.68×10^{-3}	8.36×10^{-3}
		Chlorophytes	4.00×10^{-2}	4.78×10^{-2}	4.61×10^{-2}
		Cyanobacteria	8.76×10^{-3}	9.87×10^{-19}	9.50×10^{-19}
		Diatoms	1.10×10^{-3}	4.95×10^{-4}	4.77×10^{-4}
	Front 4	Total Chl *a*	1.17×10^{-1}	1.63×10^{-1}	3.37×10^{-1}
		Dinoflagellates	0.00	4.10×10^{-18}	0.00
		Chrysophytes	6.55×10^{-3}	8.65×10^{-3}	1.68×10^{-2}
		Chlorophytes	8.39×10^{-2}	9.21×10^{-2}	2.26×10^{-1}
		Cyanobacteria	2.49×10^{-2}	3.27×10^{-2}	8.74×10^{-2}
		Diatoms	2.04×10^{-3}	3.02×10^{-3}	6.58×10^{-3}

Table A.2. (cont'd).

Cruise	Front	Algal Group	Mean Conc. Before Front (µg/L)	Mean Conc. Front (µg/L)	Mean Conc. After Front (µg/L)
Spring 2004	Front 1	Total Chl *a*	4.36×10^{-1}	3.48×10^{-1}	3.37×10^{-1}
		Prasinophytes	2.32×10^{-2}	1.85×10^{-2}	1.59×10^{-2}
		Dinoflagellates	1.96×10^{-2}	1.57×10^{-2}	1.37×10^{-2}
		Cryptophytes	3.16×10^{-2}	2.53×10^{-2}	2.25×10^{-2}
		Haptophytes	2.54×10^{-2}	2.03×10^{-2}	1.61×10^{-2}
		Chrysophytes	2.71×10^{-2}	2.17×10^{-2}	2.13×10^{-2}
		Chlorophytes	8.82×10^{-2}	7.05×10^{-2}	6.56×10^{-2}
		Cyanobacteria	1.22×10^{-1}	9.79×10^{-2}	8.42×10^{-2}
		Diatoms	1.00×10^{-1}	7.99×10^{-2}	9.85×10^{-2}
	Front 2	Total Chl *a*	1.32	1.33	1.38
		Prasinophytes	1.02×10^{-2}	1.02×10^{-2}	1.06×10^{-2}
		Dinoflagellates	1.98×10^{-1}	1.99×10^{-1}	2.06×10^{-1}
		Cryptophytes	6.11×10^{-2}	6.12×10^{-2}	6.35×10^{-2}
		Haptophytes	6.69×10^{-3}	6.70×10^{-3}	6.95×10^{-3}
		Chrysophytes	1.01×10^{-1}	1.01×10^{-1}	1.05×10^{-1}
		Chlorophytes	2.97×10^{-1}	2.98×10^{-1}	3.09×10^{-1}
		Cyanobacteria	1.24×10^{-3}	1.24×10^{-3}	1.29×10^{-3}
		Diatoms	6.46×10^{-1}	6.47×10^{-1}	6.71×10^{-1}
	Front 3	Total Chl *a*	1.59	1.62	1.67
		Prasinophytes	6.36×10^{-2}	6.50×10^{-2}	6.68×10^{-2}
		Dinoflagellates	1.83×10^{-1}	1.87×10^{-1}	1.92×10^{-1}
		Cryptophytes	1.27×10^{-1}	1.30×10^{-1}	1.34×10^{-1}
		Haptophytes	1.19×10^{-2}	1.22×10^{-2}	1.25×10^{-2}
		Chrysophytes	1.41×10^{-1}	1.44×10^{-1}	1.48×10^{-1}
		Chlorophytes	2.56×10^{-1}	2.62×10^{-1}	2.69×10^{-1}
		Cyanobacteria	1.80×10^{-3}	1.84×10^{-3}	1.89×10^{-3}
		Diatoms	8.05×10^{-1}	8.23×10^{-1}	8.46×10^{-1}
	Front 4	Total Chl *a*	7.54×10^{-1}	4.15×10^{-1}	7.54×10^{-1}
		Prasinophytes	8.07×10^{-2}	4.69×10^{-2}	8.48×10^{-2}
		Dinoflagellates	1.89×10^{-2}	1.03×10^{-2}	1.89×10^{-2}
		Cryptophytes	6.05×10^{-2}	3.15×10^{-2}	5.66×10^{-2}
		Haptophytes	4.23×10^{-2}	2.42×10^{-2}	4.43×10^{-2}
		Chrysophytes	5.33×10^{-2}	2.03×10^{-2}	3.67×10^{-2}
		Chlorophytes	7.46×10^{-2}	4.83×10^{-2}	8.83×10^{-2}
		Cyanobacteria	1.67×10^{-1}	1.15×10^{-1}	2.10×10^{-1}
		Diatoms	1.88×10^{-1}	1.18×10^{-1}	2.14×10^{-1}
	Front 5	Total Chl *a*	8.92×10^{-1}	8.61×10^{-1}	8.34×10^{-1}
		Prasinophytes	9.60×10^{-2}	9.26×10^{-2}	8.97×10^{-2}
		Dinoflagellates	2.68×10^{-2}	2.58×10^{-2}	2.50×10^{-2}
		Cryptophytes	5.92×10^{-2}	5.72×10^{-2}	5.54×10^{-2}
		Haptophytes	5.59×10^{-2}	5.40×10^{-2}	5.23×10^{-2}
		Chrysophytes	4.02×10^{-2}	3.88×10^{-2}	3.75×10^{-2}
		Chlorophytes	1.13×10^{-1}	1.09×10^{-1}	1.05×10^{-1}
		Cyanobacteria	2.53×10^{-1}	2.44×10^{-1}	2.36×10^{-1}
		Diatoms	2.47×10^{-1}	2.38×10^{-1}	2.31×10^{-1}

Table A.3. Statistical results for summer 2002 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between locations within each front. Location BF is 'before front', F is 'front', AF is 'after front'. P-values are based on a 0.05 alpha level.
*Prasinophytes were absent or below detectable concentrations at fronts 2 and 3.

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chl *a*	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515
Prasinophytes*	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	---	BF:F	---
			F:AF	---
			BF:AF	---
	3	---	BF:F	---
			F:AF	---
			BF:AF	---
Dinoflagellates	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515
Cryptophytes	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515

Table A.3. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Haptophytes	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515
Chrysophytes	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515
Chlorophytes	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515
Cyanobacteria	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515

Table A.3. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Diatoms	1	0.902	BF:F	0.996
			F:AF	0.971
			BF:AF	0.827
	2	0.003	BF:F	0.039
			F:AF	0.607
			BF:AF	0.001
	3	0.535	BF:F	0.971
			F:AF	0.999
			BF:AF	0.515

Table A.4. Statistical results for the summer 2002 cruise showing differences in algal group abundance (μg/L) between all fronts. P-values are based on a 0.05 alpha level.

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chl *a*	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Prasinophytes	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Dinoflagellates	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Cryptophytes	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Haptophytes	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Chrysophytes	0.000	1:2	0.000
		2:3	0.000
		1:3	0.011
Chlorophytes	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Cyanobacteria	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000

Table A.5. Statistical results for summer 2003 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between locations within each front. Location BF is 'before front', F is 'front', AF is 'after front'. P-values are based on a 0.05 alpha level.

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chl *a*	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.002	BF:F	0.556
			F:AF	0.889
			BF:AF	0.153
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.025	BF:F	0.015
			F:AF	0.275
			BF:AF	0.121
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.016	BF:F	0.824
			F:AF	0.399
			BF:AF	0.596
Dinoflagellates	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.006	BF:F	0.888
			F:AF	0.889
			BF:AF	0.001
	3	1.0	BF:F	---
			F:AF	---
			BF:AF	---

Table A.5. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Dinoflagellates	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.000	BF:F	0.052
			F:AF	0.000
			BF:AF	0.002
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.000	BF:F	0.000
			F:AF	0.399
			BF:AF	0.000
Cryptophytes	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.006	BF:F	0.888
			F:AF	0.889
			BF:AF	0.001
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.069	BF:F	0.125
			F:AF	0.137
			BF:AF	0.993

Table A.5. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Cryptophytes	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.000	BF:F	0.000
			F:AF	0.399
			BF:AF	0.000
Haptophytes	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.006	BF:F	0.888
			F:AF	0.889
			BF:AF	0.001
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.001	BF:F	0.029
			F:AF	0.000
			BF:AF	0.005
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.001	BF:F	0.137
			F:AF	0.399
			BF:AF	0.193

Table A.5. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chrysophytes	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.006	BF:F	0.888
			F:AF	0.889
			BF:AF	0.001
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.001	BF:F	0.023
			F:AF	0.000
			BF:AF	0.010
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9*	---	BF:F	---
			F:AF	---
			BF:AF	---
Chlorophytes	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.006	BF:F	0.888
			F:AF	0.889
			BF:AF	0.001
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996

Table A.5. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chlorophytes	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.069	BF:F	0.126
			F:AF	0.138
			BF:AF	0.994
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.000	BF:F	0.000
			F:AF	0.399
			BF:AF	0.000
Cyanobacteria	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.003	BF:F	0.560
			F:AF	0.889
			BF:AF	0.149
	3	0.950	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	4	0.495	BF:F	0.998
			F:AF	0.870
			BF:AF	0.797
	5	0.000	BF:F	0.053
			F:AF	0.285
			BF:AF	0.000
	6	0.050	BF:F	0.307
			F:AF	0.561
			BF:AF	0.180

Table A.5. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Cyanobacteria	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.000	BF:F	0.000
			F:AF	0.399
			BF:AF	0.000
Diatoms	1	0.254	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	2	0.001	BF:F	0.685
			F:AF	0.905
			BF:AF	0.327
	3	0.950	BF:F	0.522
			F:AF	0.889
			BF:AF	0.270
	4	0.495	BF:F	0.808
			F:AF	0.993
			BF:AF	0.996
	5	0.000	BF:F	0.998
			F:AF	0.870
			BF:AF	0.000
	6	0.000	BF:F	0.445
			F:AF	0.979
			BF:AF	0.000
	7	0.483	BF:F	0.999
			F:AF	0.793
			BF:AF	0.554
	8	0.001	BF:F	0.707
			F:AF	0.760
			BF:AF	0.000
	9	0.006	BF:F	0.000
			F:AF	0.399
			BF:AF	0.000

Table A.6. Statistical results for the summer 2003 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between all fronts. P-values are based on a 0.05 alpha level.

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chl *a*	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.397
		1:9	0.000
		2:3	0.397
		2:4	0.636
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.036
		2:9	0.000
		3:4	0.994
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.086
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.076
		4:9	0.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.001
		6:9	0.009
		7:8	1.000
		7:9	0.000
		8:9	0.454

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Dinoflagellates	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	1.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.024
		2:9	0.995
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.000
		3:9	0.032
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	0.938
		5:6	0.005
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.000
		6:9	0.001
		7:8	0.000
		7:9	0.036
		8:9	0.792

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Cryptophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.024
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.000
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	1.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.000
		6:9	0.430
		7:8	0.000
		7:9	0.000
		8:9	0.000

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Haptophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.024
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	1.000
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	0.000
		5:6	0.001
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.000
		6:9	0.000
		7:8	0.000
		7:9	0.000
		8:9	0.000

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chrysophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.024
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	1.000
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	0.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.000
		6:9	0.000
		7:8	0.000
		7:9	0.000
		8:9	0.000

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chlorophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.024
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.000
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	1.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.000
		6:9	0.000
		7:8	0.000
		7:9	0.528
		8:9	0.000

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Cyanobacteria	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.322
		1:9	0.000
		2:3	1.000
		2:4	0.282
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.014
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.011
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.036
		4:9	0.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.000
		6:8	0.012
		6:9	0.000
		7:8	1.000
		7:9	1.000
		8:9	1.000

Table A.6. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Diatoms	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.009
		2:7	0.040
		2:8	0.000
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	1.000
		3:7	0.000
		3:8	0.000
		3:9	0.000
		4:5	0.000
		4:6	0.000
		4:7	0.000
		4:8	0.000
		4:9	0.000
		5:6	0.000
		5:7	0.000
		5:8	0.000
		5:9	1.000
		6:7	0.033
		6:8	0.000
		6:9	0.000
		7:8	0.000
		7:9	0.000
		8:9	0.000

Table A.7. Statistical results for fall 2003 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between locations within each front. Location BF is 'before front', F is 'front', AF is 'after front'. P-values are based on a 0.05 alpha level.
* Absent or below the limit of detection at fronts 1, 2, and 4.

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chl *a*	1	0.601	BF:F	0.601
			F:AF	0.294
			BF:AF	0.673
	2	0.217	BF:F	0.701
			F:AF	0.676
			BF:AF	0.980
	3	0.313	BF:F	0.625
			F:AF	0.160
			BF:AF	0.502
	4	0.000	BF:F	0.515
			F:AF	0.023
			BF:AF	0.000
Dinoflagellates	1*	---	BF:F	---
			F:AF	---
			BF:AF	---
	2*	---	BF:F	---
			F:AF	---
			BF:AF	---
	3	0.060	BF:F	0.004
			F:AF	0.160
			BF:AF	0.006
	4*	---	BF:F	---
			F:AF	---
			BF:AF	---
Chrysophytes	1	1.000	BF:F	---
			F:AF	---
			BF:AF	---
	2	0.217	BF:F	0.701
			F:AF	0.676
			BF:AF	0.980
	3	0.064	BF:F	0.005
			F:AF	0.160
			BF:AF	0.013
	4	0.000	BF:F	0.425
			F:AF	0.007
			BF:AF	0.000

Table A.7. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chlorophytes	1	0.601	BF:F	0.601
			F:AF	0.294
			BF:AF	0.673
	2	0.048	BF:F	0.573
			F:AF	0.676
			BF:AF	0.485
	3	0.064	BF:F	0.006
			F:AF	0.160
			BF:AF	0.031
	4	0.000	BF:F	0.987
			F:AF	0.063
			BF:AF	0.000
Cyanobacteria	1	0.601	BF:F	0.601
			F:AF	0.294
			BF:AF	0.673
	2	0.359	BF:F	0.614
			F:AF	0.676
			BF:AF	0.099
	3	0.002	BF:F	0.004
			F:AF	0.160
			BF:AF	0.004
	4	0.000	BF:F	0.890
			F:AF	0.071
			BF:AF	0.000
Diatoms	1	0.601	BF:F	0.601
			F:AF	0.294
			BF:AF	0.673
	2	0.029	BF:F	0.317
			F:AF	0.676
			BF:AF	0.134
	3	0.001	BF:F	0.004
			F:AF	0.160
			BF:AF	0.003
	4	0.000	BF:F	0.505
			F:AF	0.027
			BF:AF	0.000

Table A.8. Statistical results for the fall 2003 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between all fronts. P-values are based on a 0.05 alpha level.
* Algal groups were absent or below the limit of detection.

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chl *a*	0.000	1:2	0.000
		1:3	0.262
		1:4	0.001
		2:3	0.000
		2:4	0.987
		3:4	0.001
Dinoflagellates	0.000	1:2*	---
		1:3	0.000
		1:4	0.892
		2:3	0.000
		2:4	0.892
		3:4	0.000
Chrysophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		2:3	0.005
		2:4	0.002
		3:4	0.028
Chlorophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.018
		2:3	0.000
		2:4	0.741
		3:4	0.000
Cyanobacteria	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		2:3	0.000
		2:4	0.002
		3:4	0.000

Table A.8. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Diatoms	0.000	1:2	0.000
		1:3	0.000
		1:4	0.134
		2:3	0.000
		2:4	0.002
		3:4	0.000

Table A.9. Statistical results for spring 2004 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between locations within each front. Location BF is 'before front', F is 'front', AF is 'after front'. P-values are based on a 0.05 alpha level.

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chl *a*	1	0.004	BF:F	0.473
			F:AF	0.991
			BF:AF	0.001
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.275	BF:F	0.747
			F:AF	0.747
			BF:AF	1.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000
Prasinophytes	1	0.003	BF:F	0.473
			F:AF	0.744
			BF:AF	0.002
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.001	BF:F	0.788
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.469
			F:AF	0.521
			BF:AF	0.000

Table A.9. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Dinoflagellates	1	0.003	BF:F	0.473
			F:AF	0.789
			BF:AF	0.001
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.275	BF:F	0.747
			F:AF	0.747
			BF:AF	1.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000
Cryptophytes	1	0.003	BF:F	0.473
			F:AF	0.837
			BF:AF	0.001
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.000	BF:F	0.691
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000

Table A.9. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Haptophytes	1	0.003	BF:F	0.473
			F:AF	0.590
			BF:AF	0.005
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.001	BF:F	0.785
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000
Chrysophytes	1	0.005	BF:F	0.473
			F:AF	0.999
			BF:AF	0.002
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.000	BF:F	0.467
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000

Table A.9. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Chlorophytes	1	0.003	BF:F	0.473
			F:AF	0.936
			BF:AF	0.001
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.001	BF:F	0.877
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000
Cyanobacteria	1	0.003	BF:F	0.473
			F:AF	0.756
			BF:AF	0.002
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.001	BF:F	0.916
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000

Table A.9. (cont'd).

Pigment/ Algal Group	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Diatoms	1	0.247	BF:F	0.473
			F:AF	0.587
			BF:AF	0.999
	2	0.331	BF:F	1.000
			F:AF	0.274
			BF:AF	0.493
	3	0.011	BF:F	0.217
			F:AF	0.021
			BF:AF	0.005
	4	0.001	BF:F	0.850
			F:AF	0.747
			BF:AF	0.000
	5	0.000	BF:F	0.468
			F:AF	0.521
			BF:AF	0.000

Table A.10. Statistical results for the spring 2004 cruise showing differences in algal group abundance (μg/L) and diversity values (Shannon-Weaver Index) between all fronts. P-values are based on a 0.05 alpha level.

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chl *a*	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.002
Prasinophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.004
		3:5	0.000
		4:5	0.008
Dinoflagellates	0.000	1:2	0.000
		1:3	0.000
		1:4	0.858
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.000

Table A.10. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Cryptophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.197
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	1.000
Haptophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.000
Chrysophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.742

Table A.10. (cont'd).

Pigment/ Algal Group	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Chlorophytes	0.000	1:2	0.000
		1:3	0.000
		1:4	1.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.000
Cyanobacteria	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.000
Diatoms	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.000

Table A.11. Statistical results showing differences in diversity values (Shannon-Weaver Index) between locations within each front for all cruises. Location BF is 'before front', F is 'front', AF is 'after front'. Kruskal-Wallis test showed no significant difference between front locations, therefore, no Dunnett T3 tests were performed

Cruise	Front	Kruskal-Wallis (p-value)	Location Pair	Dunnett T3 (p-value)
Summer 2002	1	1.000	BF:F	---
			F:AF	---
			BF:AF	---
	2	1.000	BF:F	---
			F:AF	---
			BF:AF	---
	3	1.000	BF:F	---
			F:AF	---
			BF:AF	---
Summer 2003	Diversity values were identical between locations with all fronts			
Fall 2003	1	1.000	BF:F	---
			F:AF	---
			BF:AF	---
	2	0.061	BF:F	0.100
			F:AF	1.000
			BF:AF	0.100
	3	0.001	BF:F	0.004
			F:AF*	---
			BF:AF	0.004
	4	0.000	BF:F	0.317
			F:AF	0.503
			BF:AF	0.098
Spring 2004	1	0.137	BF:F*	---
			F:AF	0.210
			BF:AF	0.210
	2	1.000	BF:F*	---
			F:AF*	---
			BF:AF*	---
	3	1.000	BF:F*	---
			F:AF*	---
			BF:AF*	---
	4	0.000	BF:F	0.140
			F:AF	0.750
			BF:AF	---
	5	1.000	BF:F*	---
			F:AF*	---
			BF:AF*	---

.

Table A.12. Statistical results for the summer 2002 cruise showing differences in diversity values (Shannon-Weaver Index) between all fronts. P-values are based on a 0.05 alpha level.

Cruise	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Summer 2002	0.000	1:2	0.000
		2:3	0.000
		1:3	0.000
Summer 2003	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		1:5	0.000
		1:6	0.000
		1:7	0.000
		1:8	0.000
		1:9	0.000
		2:3	0.000
		2:4	0.000
		2:5	0.000
		2:6	0.000
		2:7	0.000
		2:8	0.000
		2:9	0.000
		3:4	0.000
		3:5	0.000
		3:6	0.000
		3:7	0.000
		3:8	0.000
		3:9	0.000
		4:5	0.000
		4:6	0.024
		4:7	0.000
		4:8	0.000
		4:9	0.000
		5:6	0.667
		5:7	0.000
		5:8	0.000
		5:9	0.000
		6:7	0.038
		6:8	0.000
		6:9	0.000
		7:8	0.000
		7:9	0.000
		8:9	0.000

Table A.12. (cont'd).

Cruise	Kruskal-Wallis (p-value)	Front Pair	Dunnett T3 (p-value)
Fall 2003	0.000	1:2	0.000
		1:3	0.000
		1:4	0.000
		2:3	0.782
		2:4	0.000
		3:4	0.000
Spring 2004	0.000	1:2	0.000
		1:3	0.000
		1:4	0.934
		1:5	0.992
		2:3	0.000
		2:4	0.000
		2:5	0.000
		3:4	0.000
		3:5	0.000
		4:5	0.165

APPENDIX B

Satellite images* of sea surface temperature showing frontal zones identified for the summer 2002 & 2003 cruise, the fall 2003 cruise and the spring 2004 cruise.

*Reprinted and posted on the web with permission from Johns Hopkins University Applied Physics Laboratory.

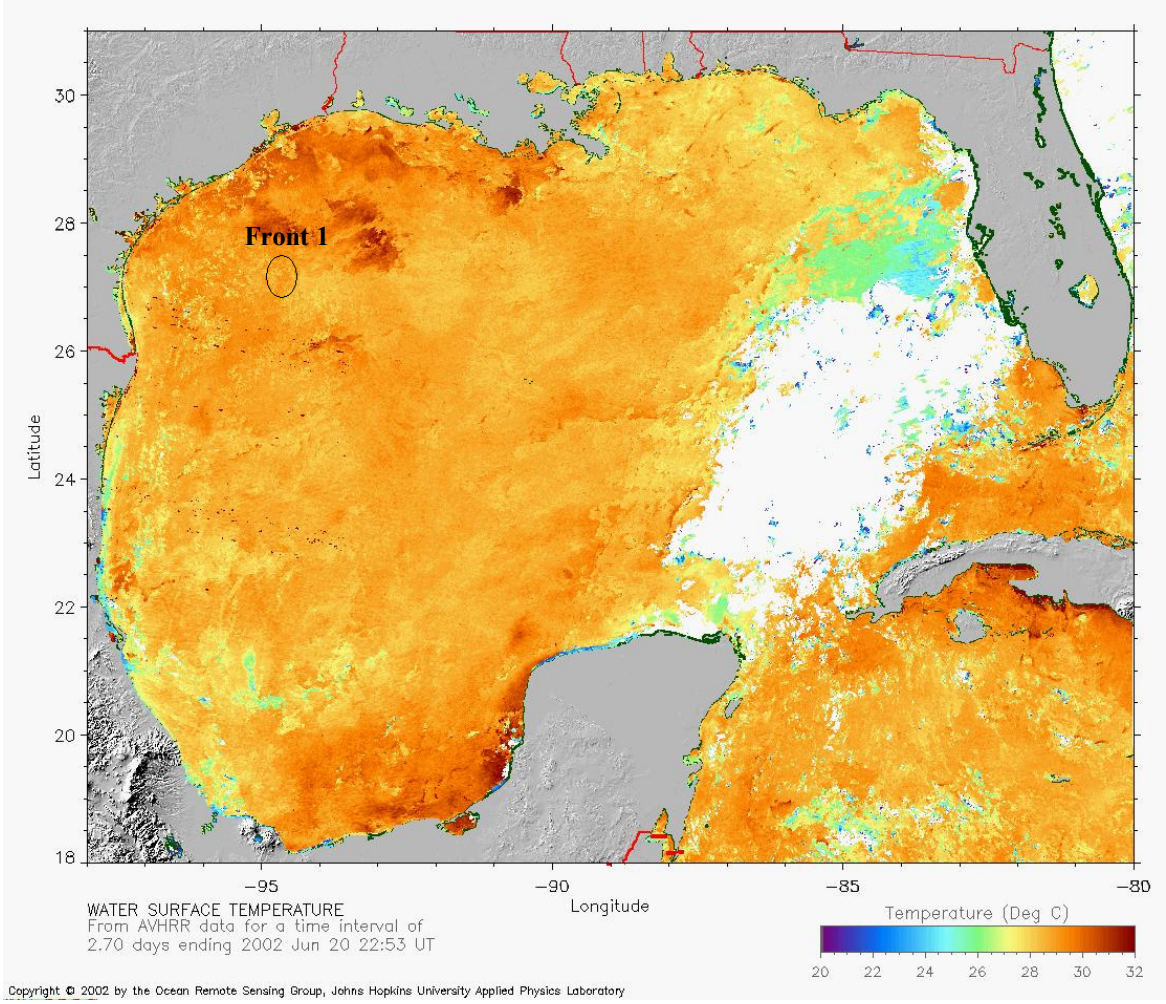

Figure B.1. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2002 cruise. Front 1 – June 20, 2002.

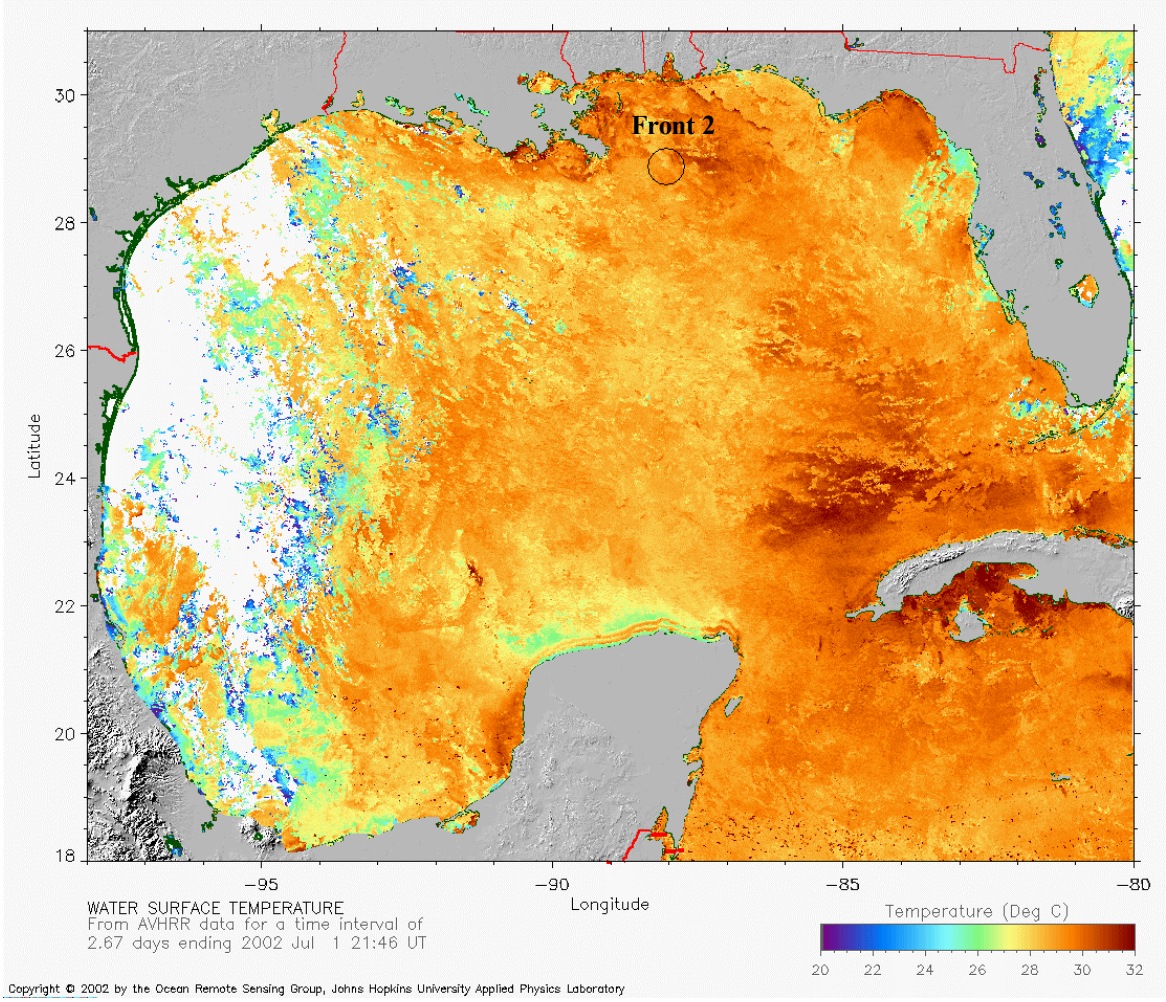

Figure B.2. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2002 cruise. Front 2 - July 1, 2002.

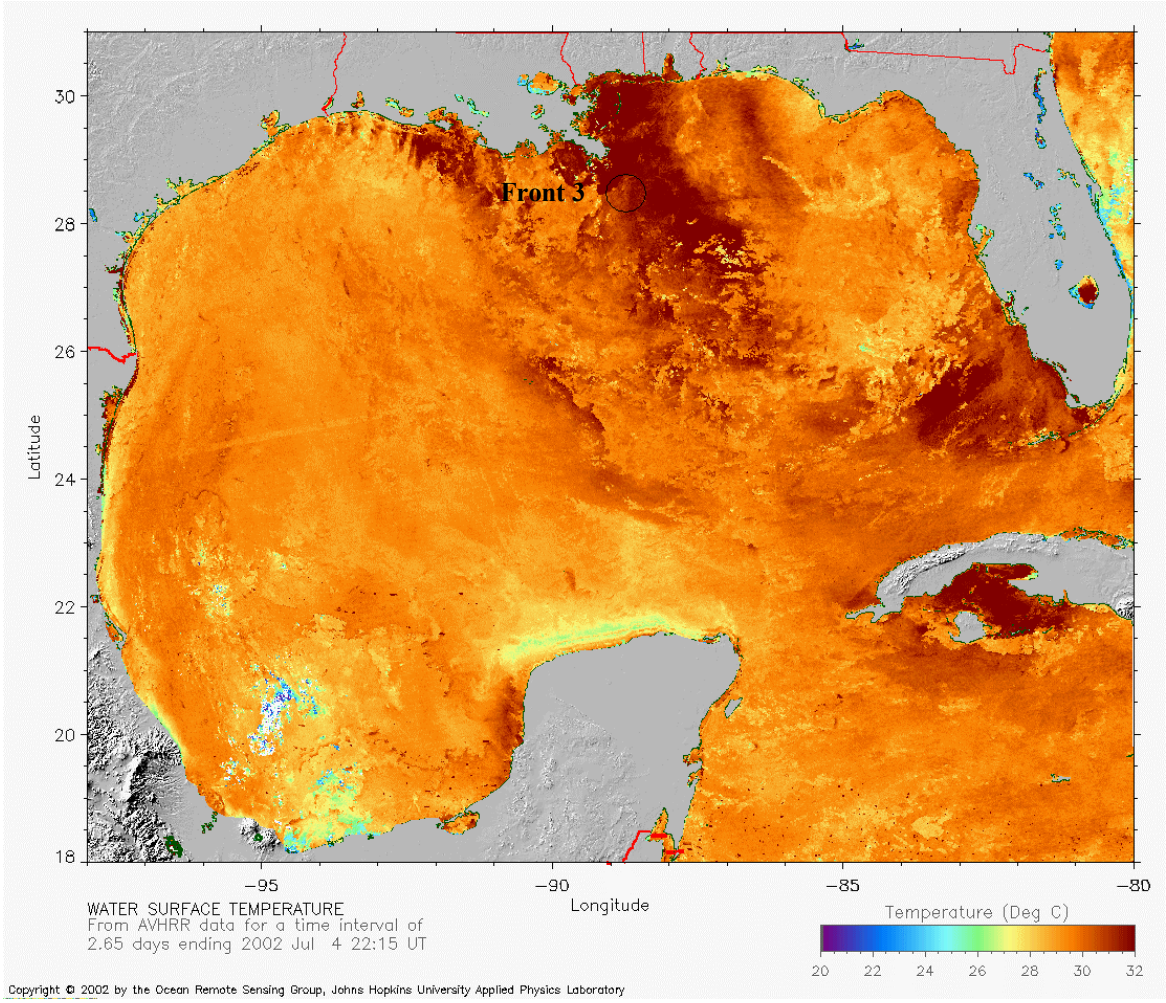

Figure B.3. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2002 cruise. Front 3 - July 4, 2002.

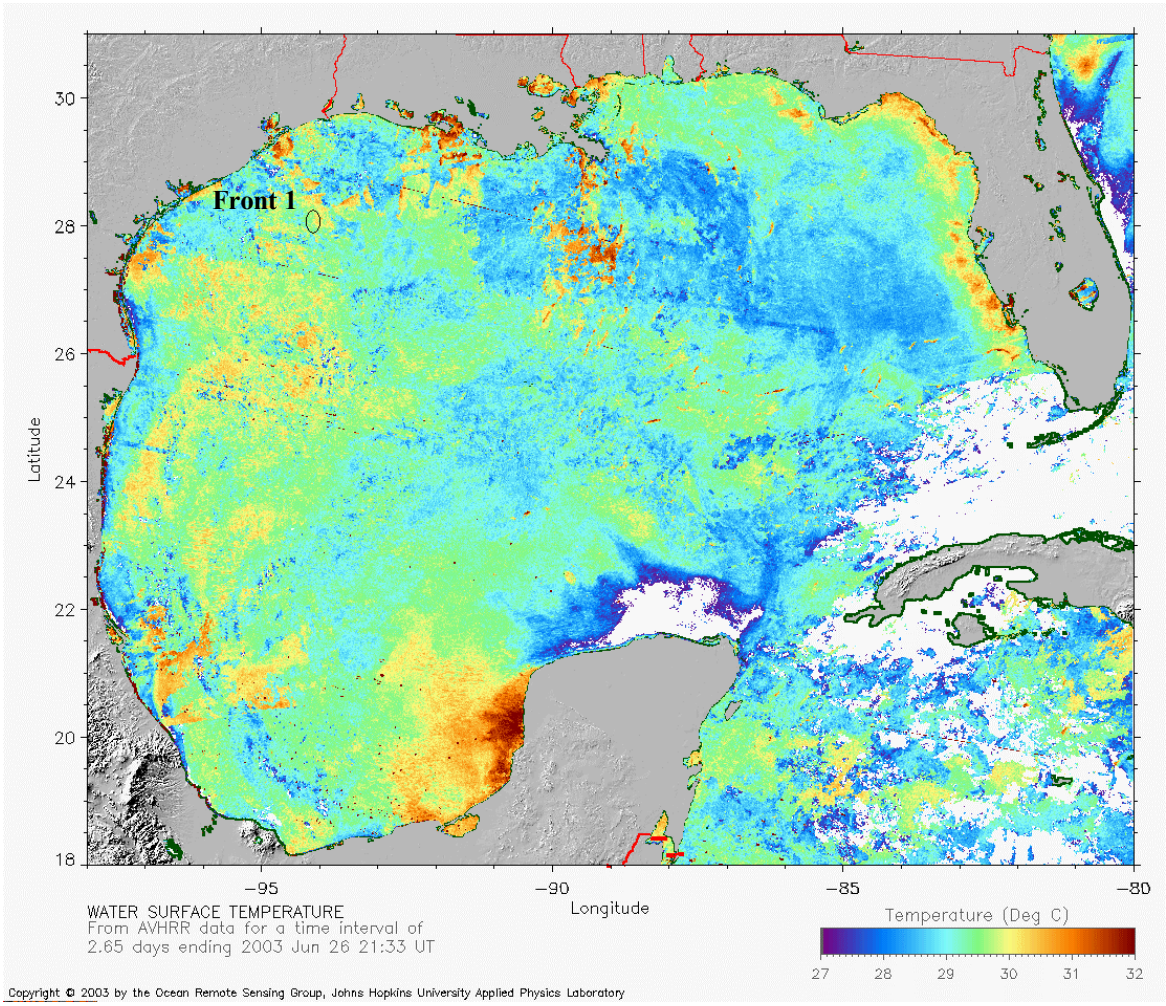

Figure B.4. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 1 – June 26, 2003.

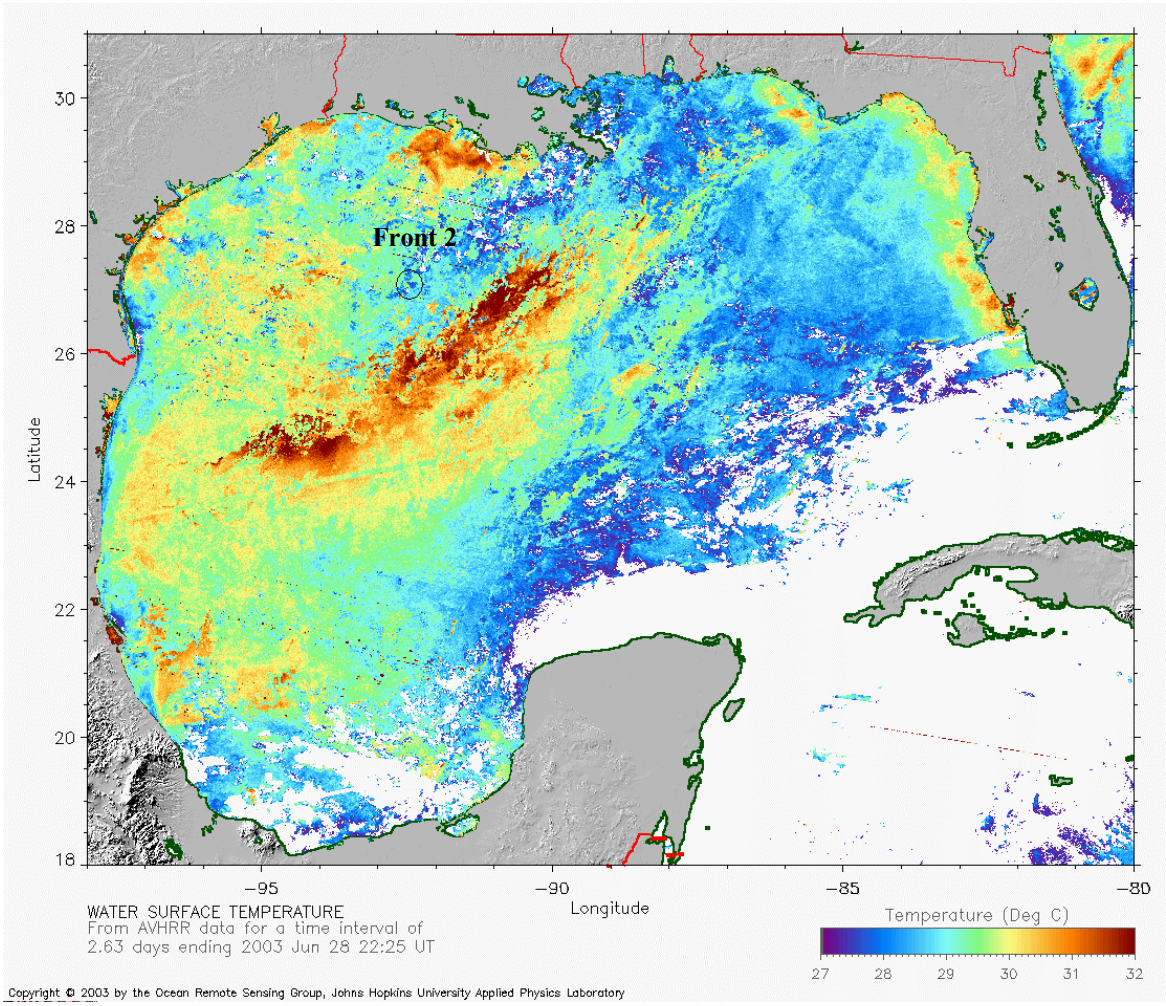

Figure B.5. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 2 – June 28, 2003.

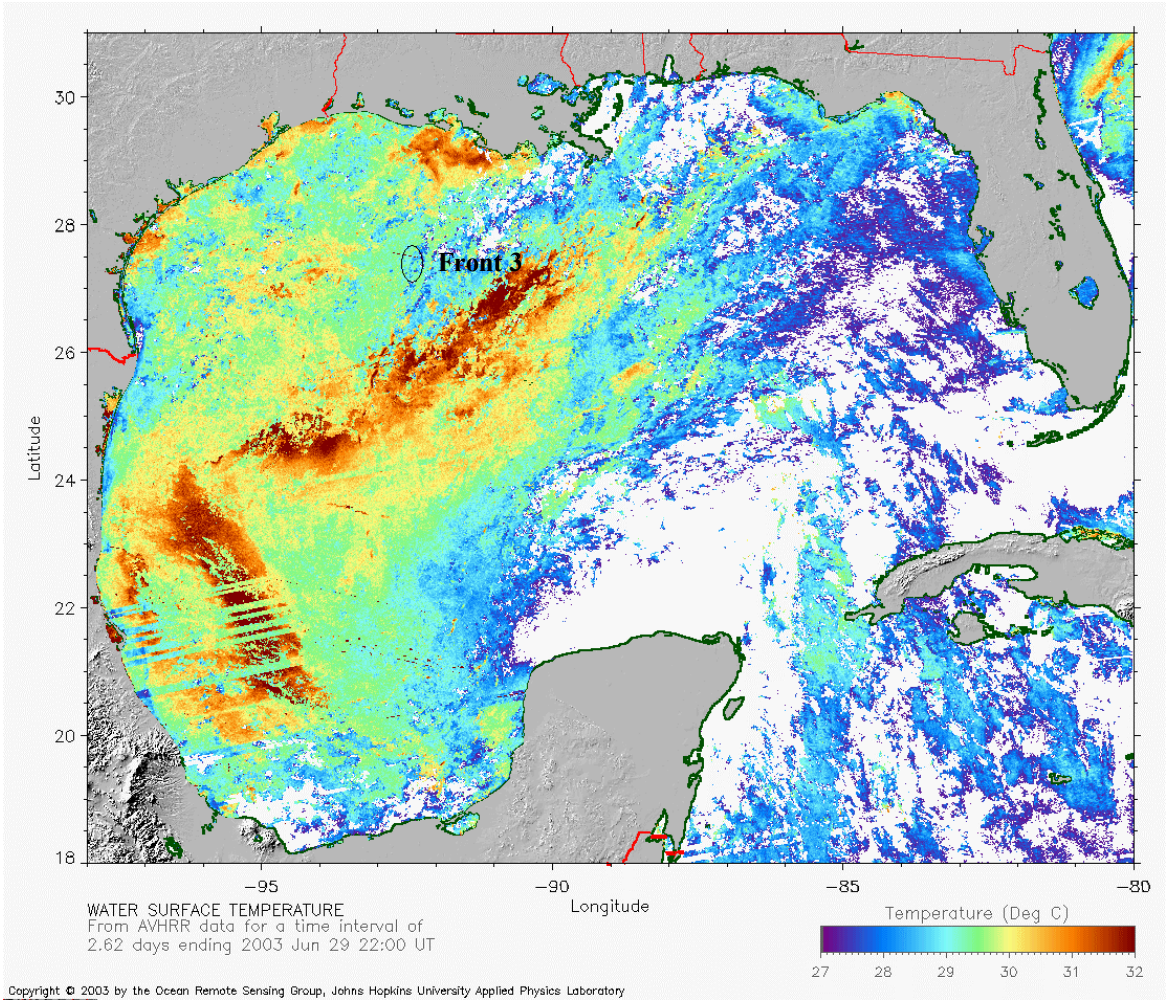

Figure B.6. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 3 – June 29, 2003.

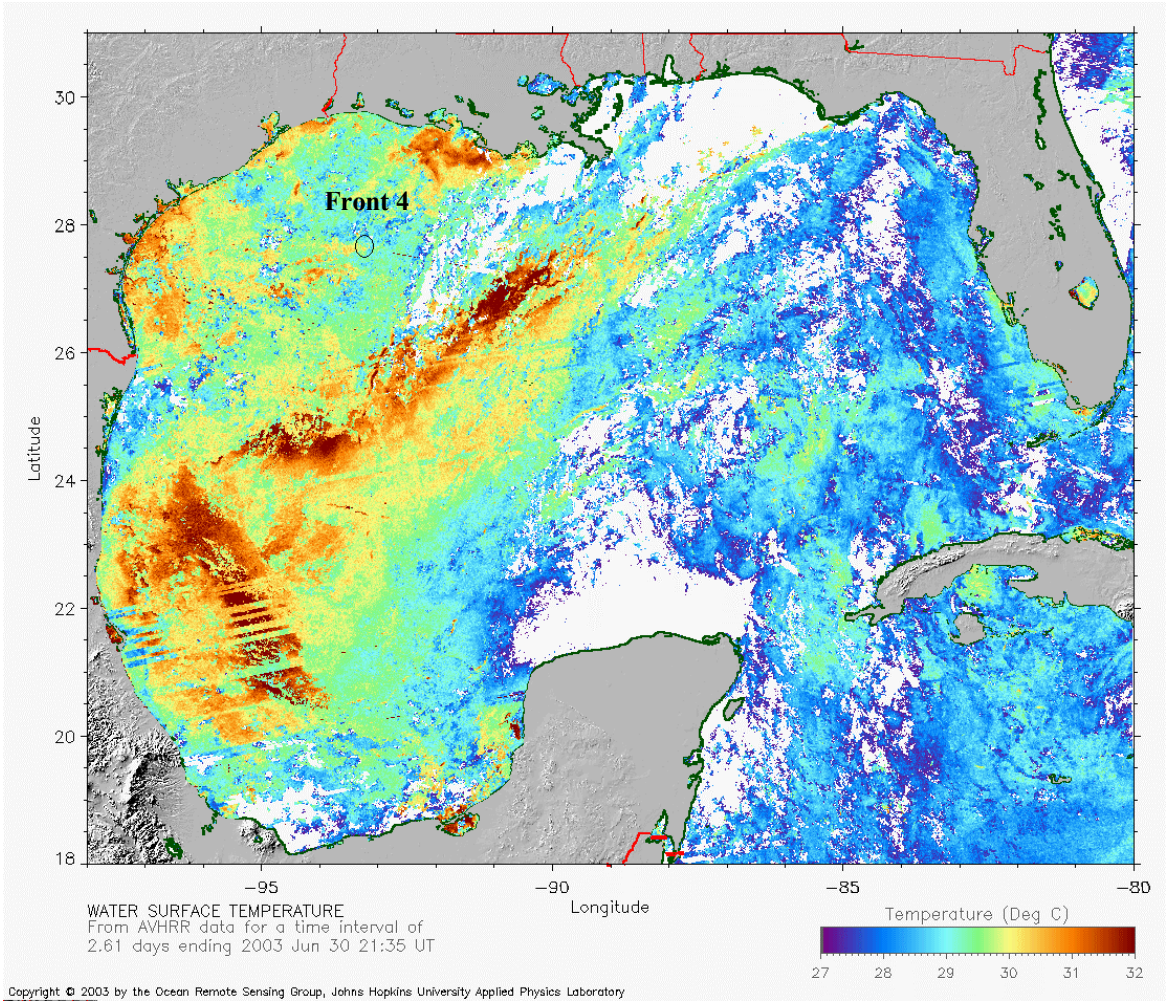

Figure B.7. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 4 – June 30, 2003.

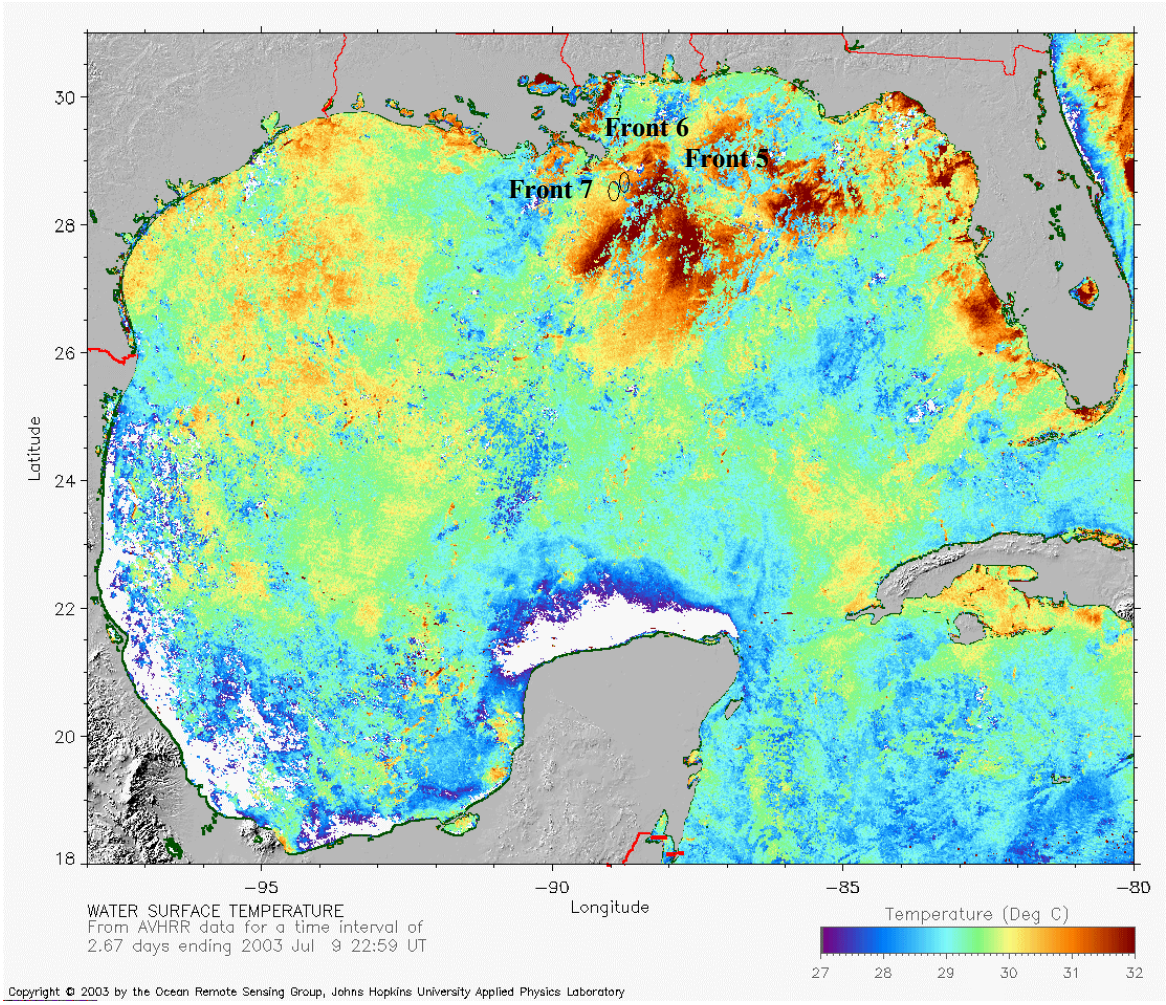

Figure B.8. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Fronts 5, 6, & 7 – July 9, 2003.

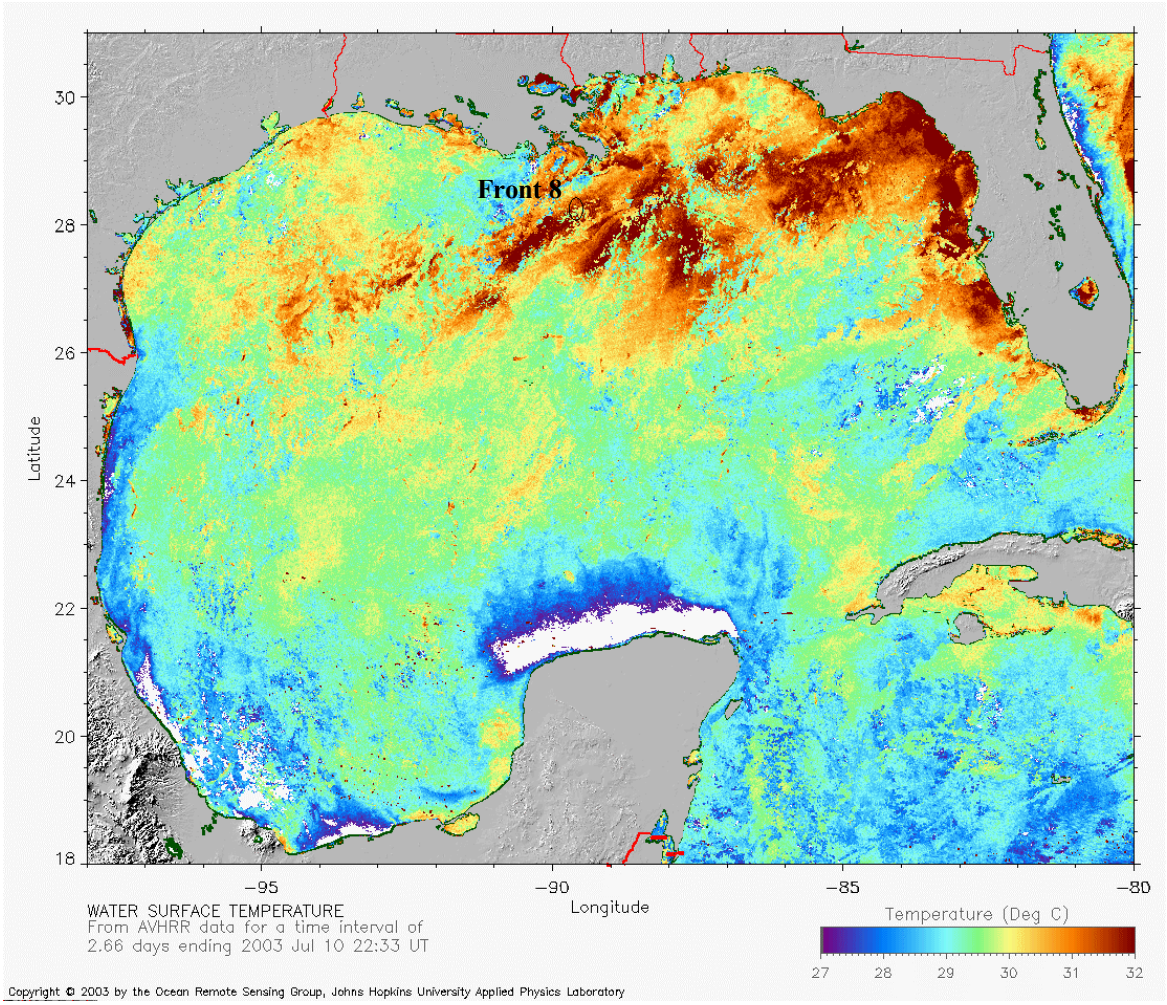

Figure B.9. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 8 – July 10, 2003.

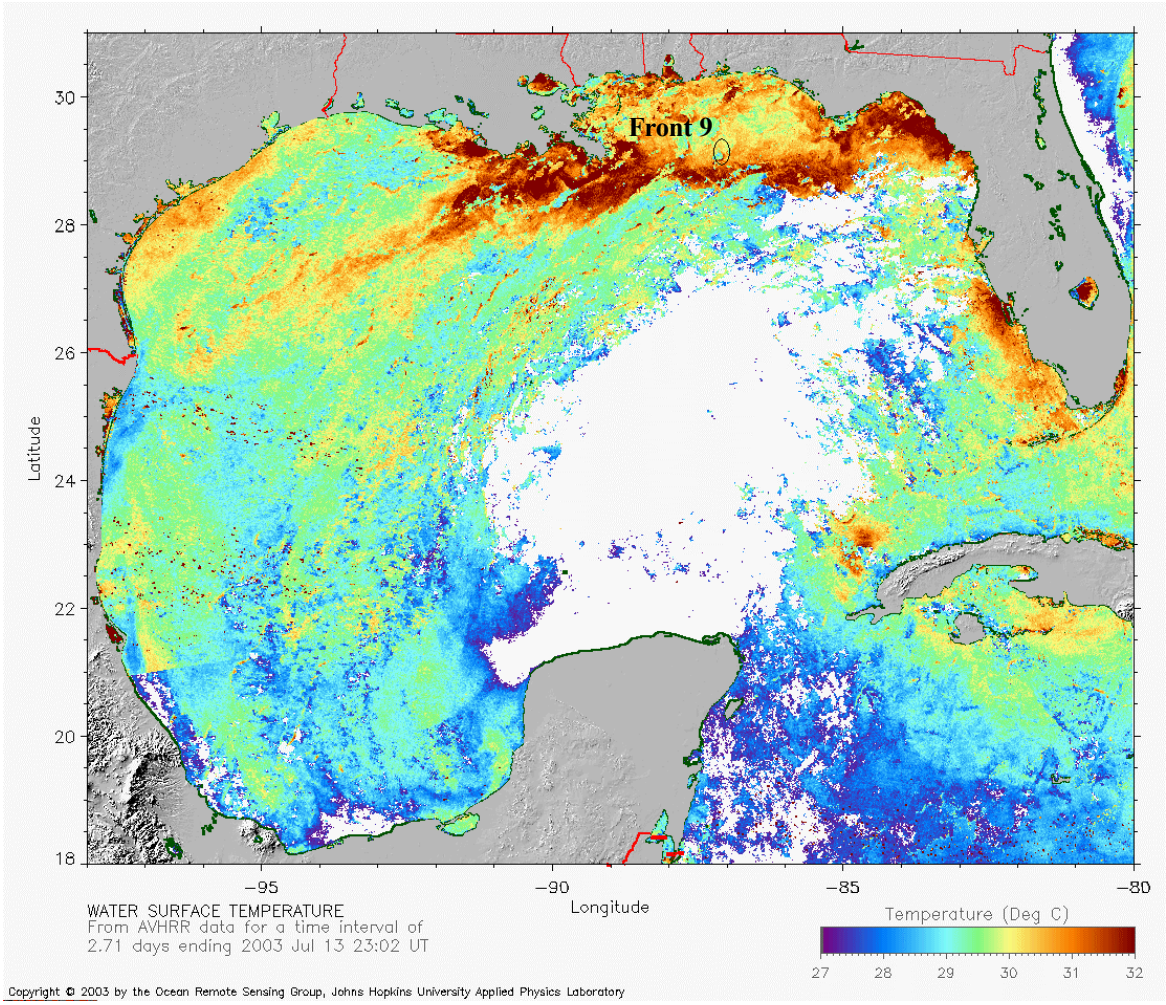

Figure B.10. Satellite (AVHRR) image of sea surface temperature (3-day composite) during summer 2003 cruise. Front 9 – July 13, 2003.

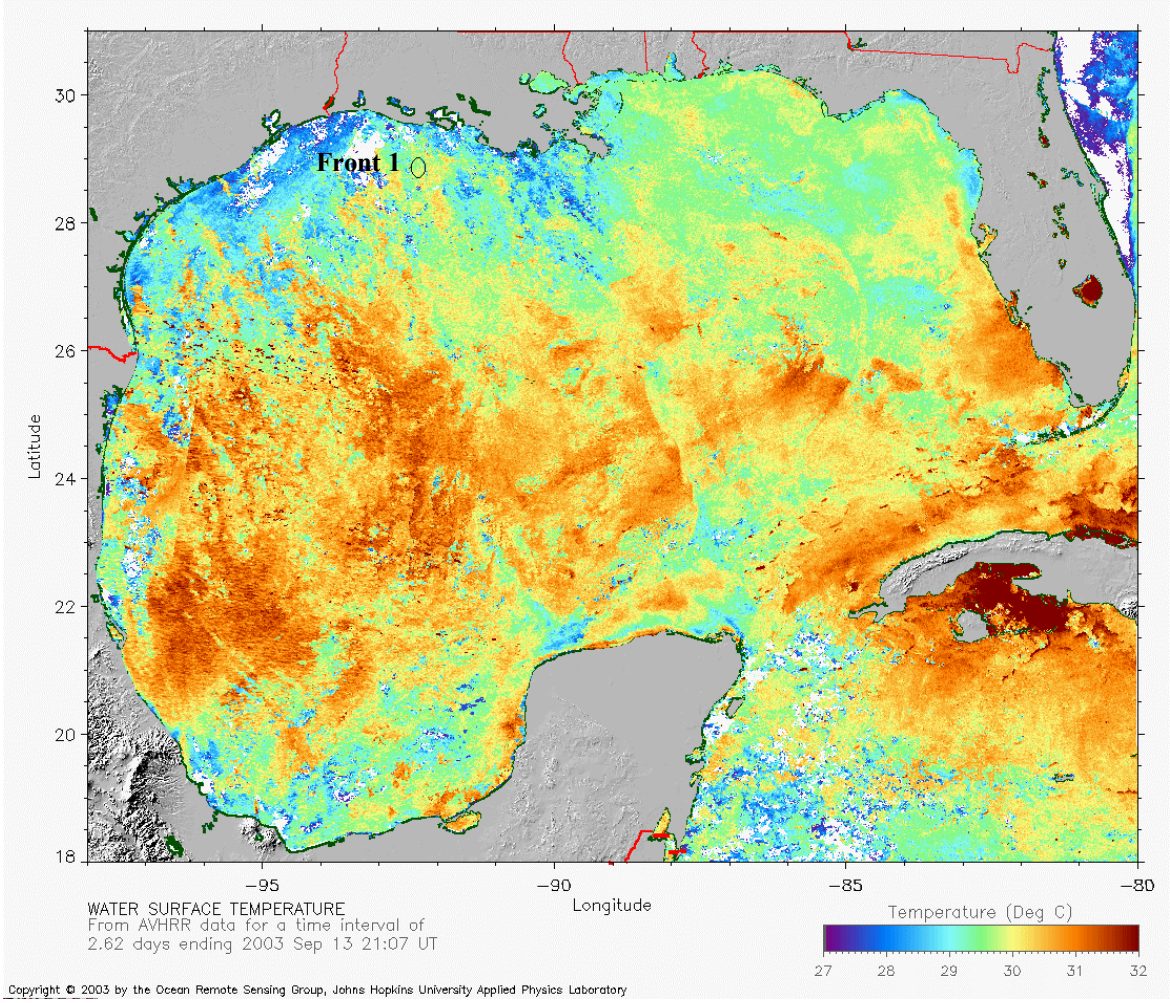

Figure B.11. Satellite (AVHRR) image of sea surface temperature (3-day composite) during fall 2003 cruise. Front 1 – September 13, 2003.

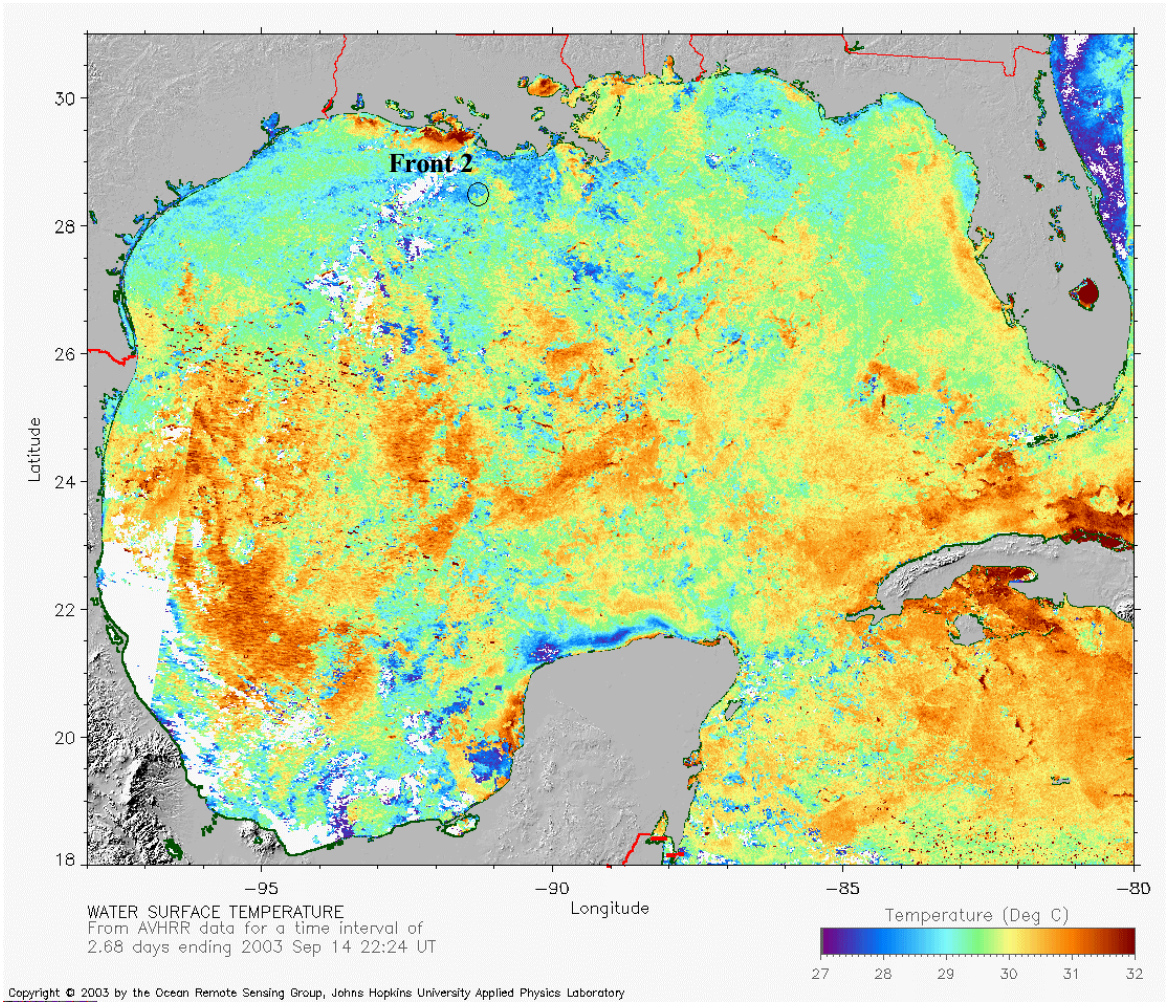

Figure B.12. Satellite (AVHRR) image of sea surface temperature (3-day composite) during fall 2003 cruise. Front 2 – September 14, 2003.

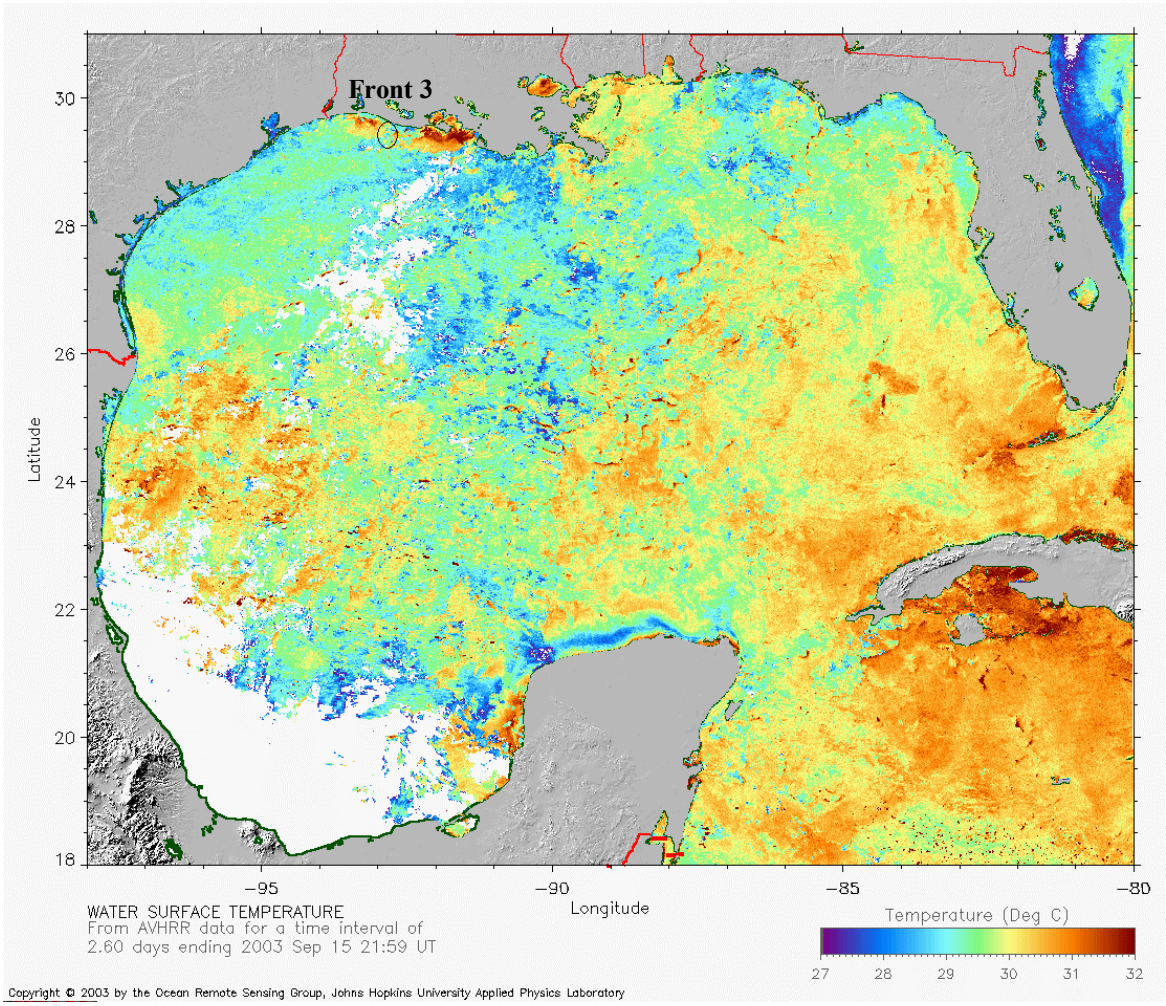

Figure B.13. Satellite (AVHRR) image of sea surface temperature (3-day composite) during fall 2003 cruise. Front 3 – September 15, 2003.

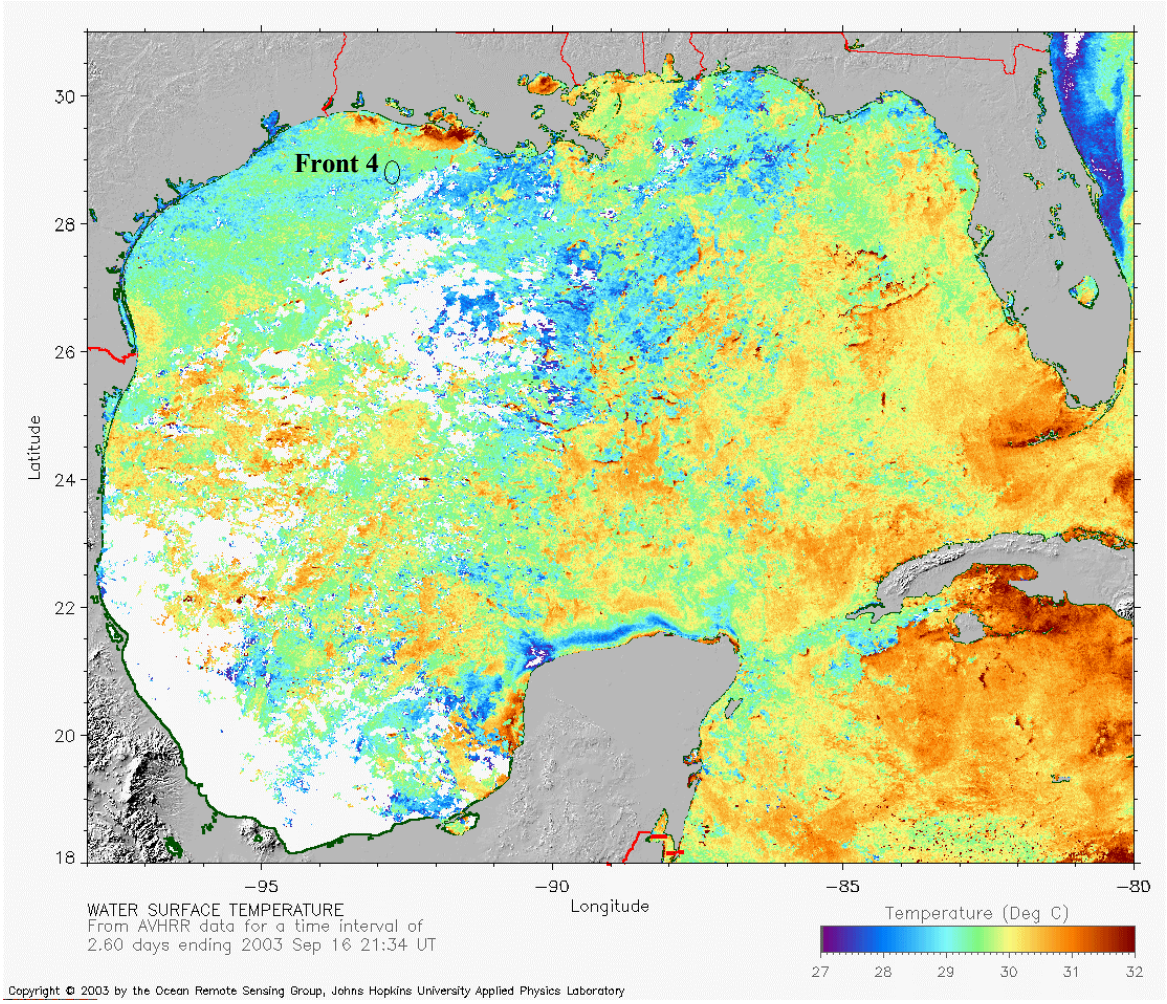

Figure B.14. Satellite (AVHRR) image of sea surface temperature (3-day composite) during fall 2003 cruise. Front 4 – September 16, 2003.

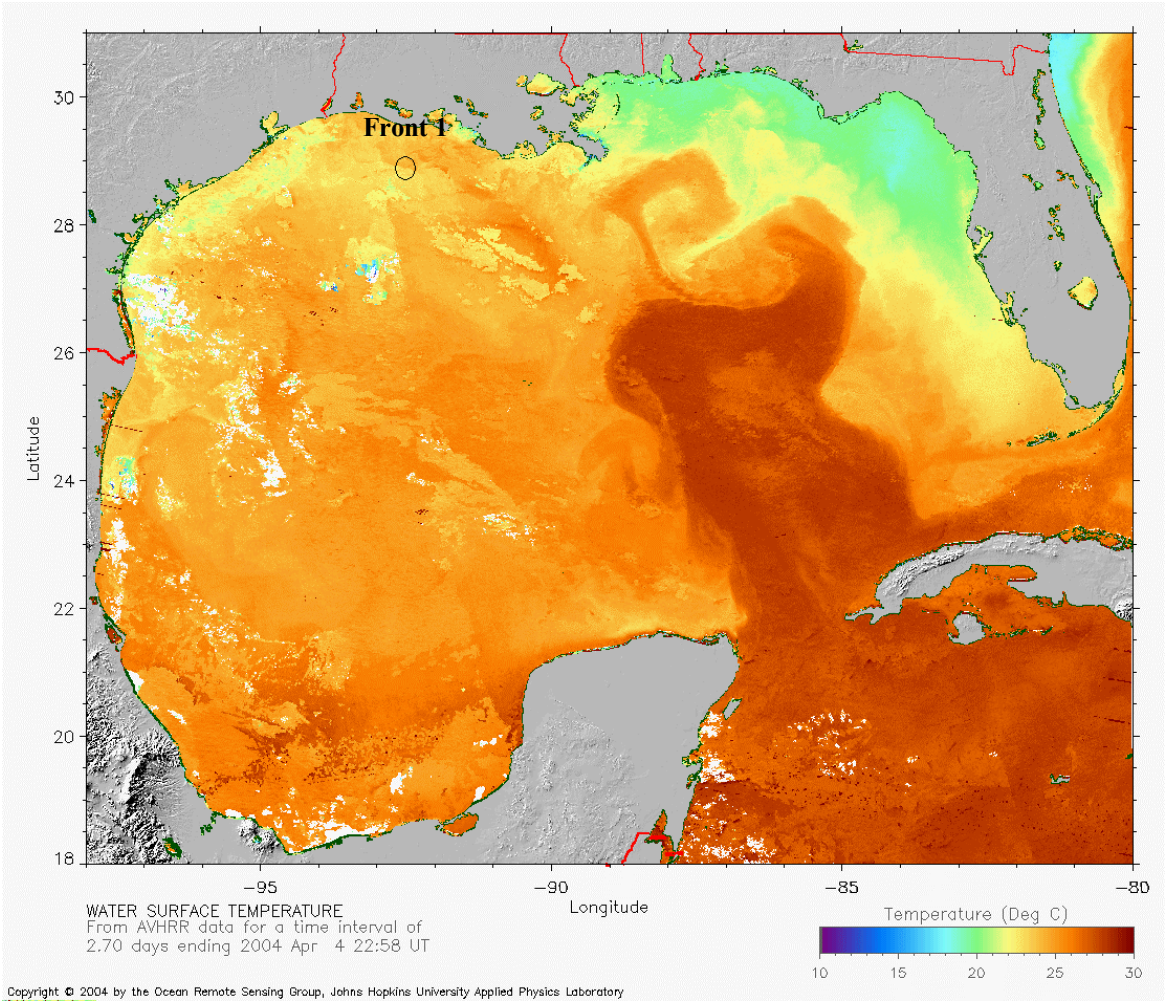

Figure B.15. Satellite (AVHRR) image of sea surface temperature (3-day composite) during spring 2004 cruise. Front 1 – April 4, 2004.

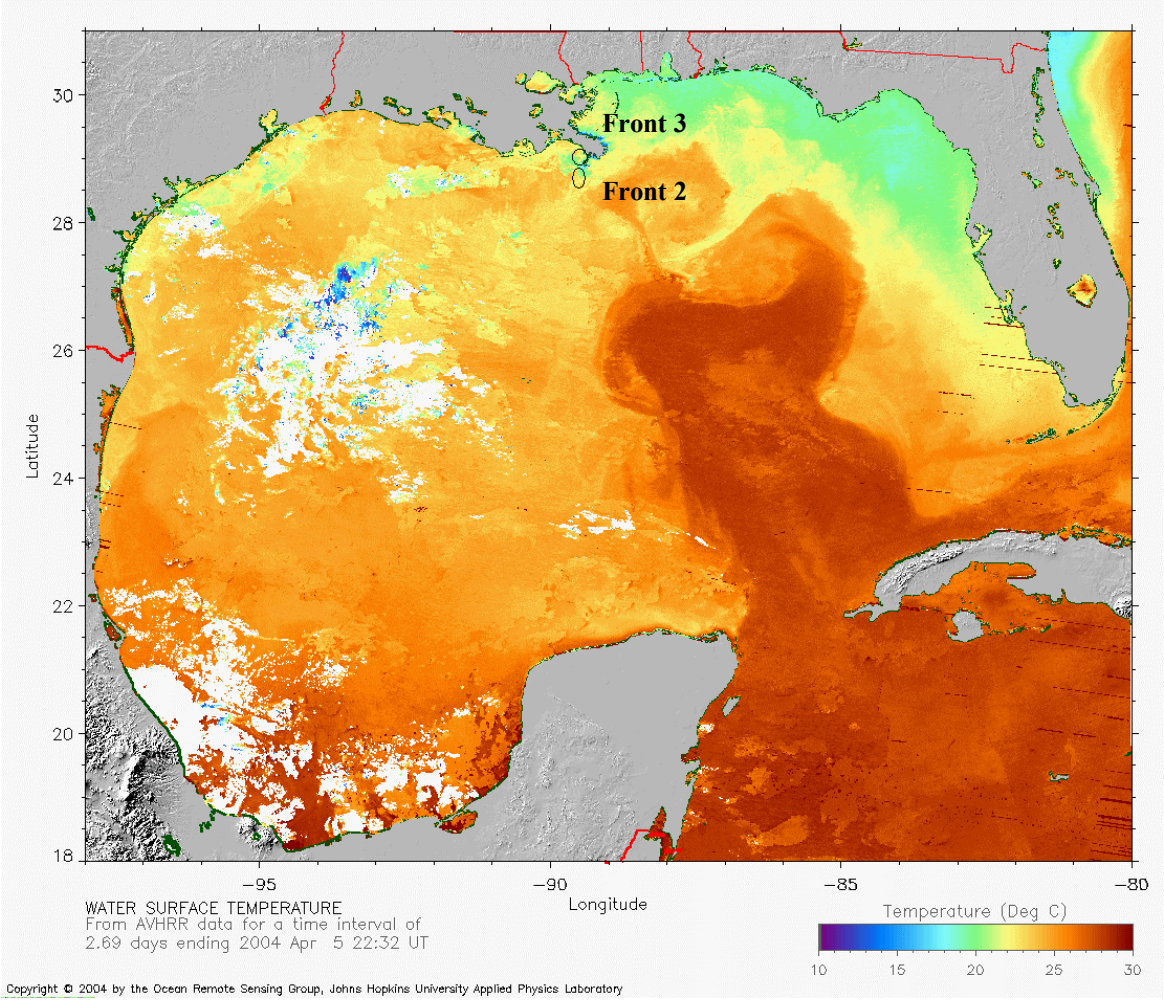

Figure B.16. Satellite (AVHRR) image of sea surface temperature (3-day composite) during spring 2004 cruise. Fronts 2 & 3 – April 5, 2004.

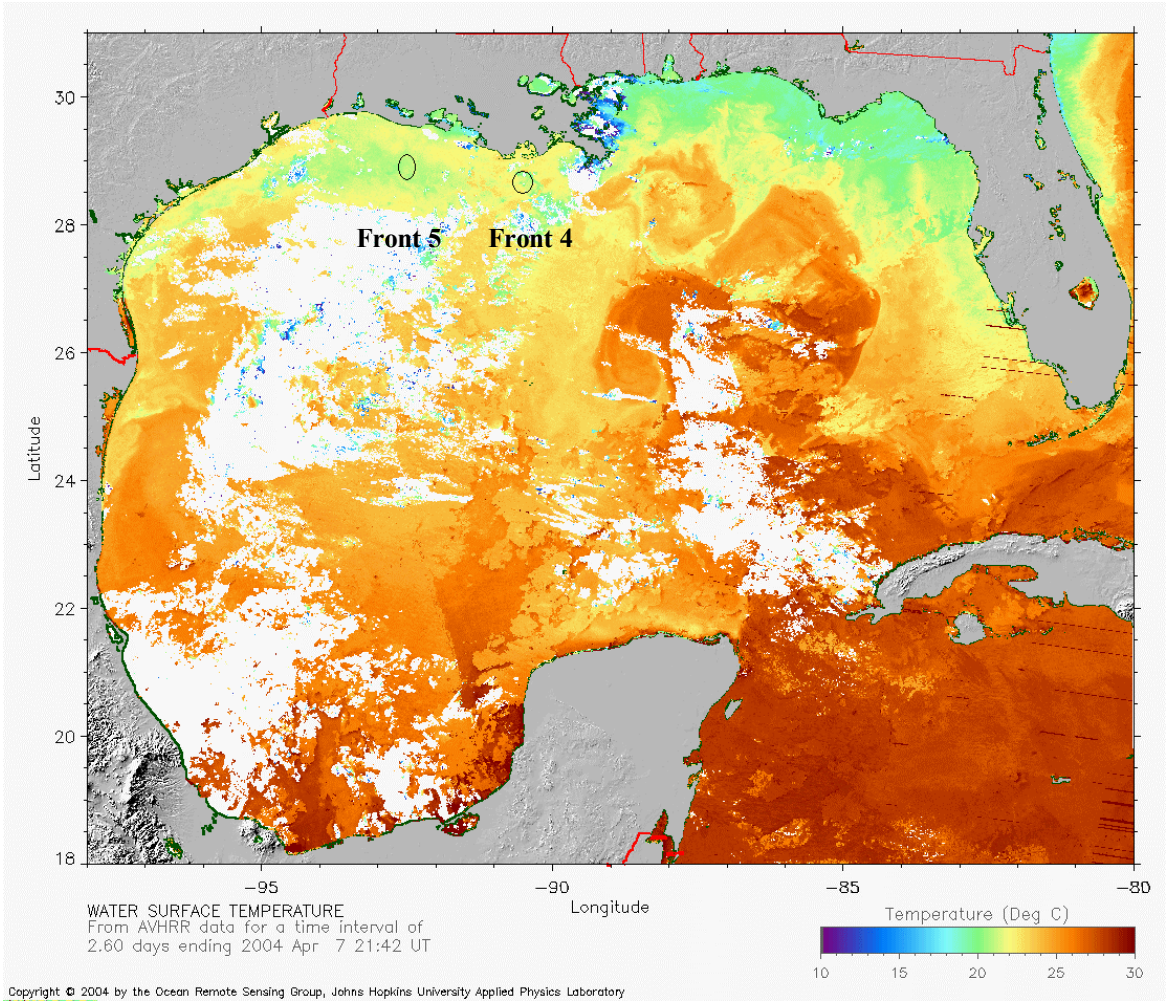

Figure B.17. Satellite (AVHRR) image of sea surface temperature (3-day composite) during spring 2004 cruise. Fronts 4 & 5 – April 7, 2004.

VITA

Alicia Salazar was born on February 2, 1973 in Cameron County Texas to Maria and Bernabe Salazar. She grew up in Houston, attended the High School for Law Enforcement and Criminal Justice from which she graduated in 1991. She received a Bachelor of Science in marine biology from Spring Hill College in the fall of 1994. She began her graduate education at Texas A&M University in the spring of 2002. Alicia may be contacted through her parents' home at 2308 Hollow Brook Ln., Conroe, TX 77384.